STARS
AND
PLANETS

GIORGIO
ABETTI

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STARS and PLANETS

Giorgio Abetti

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Translated from the third Italian edition by Dr. V. Barocas

Stars and Planets are two classes of celestial objects which are different, both in their physical conditions and in their distance from the Earth. Stars, which in the old days were known as 'fixed', and planets, which were considered to be 'wandering stars', are both part of the greater system known as the Galaxy. Our solar system, which is composed of our own star, the Sun, and its family of planets, is part of this greater system.

The study of the celestial bodies was at first limited to the study of their position in the sky and to the laws which regulate their motion in space. Nearly a century ago the introduction of spectral analysis made possible the study of the physical conditions of these celestial objects. This enabled astronomers to understand the constitution of the stars and led to the important discovery of the existence of the unity of matter throughout the whole observable universe.

More recent developments in radio astronomy and the advent of space probes have made it possible to widen even further our knowledge of the conditions prevailing in interplanetary space, and have opened new horizons in the study of the constitution of the planets forming our solar system.

This book tries to explain in a simple form the principles followed in the study of the constitution of both stars and planets. It outlines the observations, their interpretations and the theories which are generally accepted nowadays, and it attempts to discuss the many mysterious questions relating to the universe.

Above: Sunspots. A photograph taken by Stratascope I. *Below.* The Moon from an altitude of 115 miles. Ranger 9 picture. Both illustrations by courtesy of the United States Information Service.

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by Giorgio Abetti

THE SUN

Translated by J. B. Sidgwick

'. . . this book provides the most complete account available of general descriptive solar physics. It is of great value to the meteorologist, the biologist, and any other scientist from another discipline who needs to consider the radiations from the sun, as well as to the layman interested in astronomy. The professional astronomer will also find it most suitable as a general survey of solar observations. . . .' *Science Progress*

'. . . has the outstanding merits of being comprehensive and readable . . . a fine work of reference and an imaginative account informed by mature learning.' *Listener*

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by Giorgio Abetti and Margherita Hack

NEBULAE AND GALAXIES

Translated by Dr. V. Barocas

'Beginning with a brief history of the subject, the authors devote a valuable chapter to the methods and instruments now in use; clear explanations and definitions are given where necessary. The well-defined planetary nebulae have a long chapter to themselves, and the subsequent chapters deal in turn with the bright and dark nebulae of the Milky Way, with the structure of our own galaxy, and with our present knowledge of the external galaxies and of the Universe as a whole. An unusual feature of great interest is a detailed description of many of the individual nebulae. There is an admirable collection of plates and explanatory diagrams, together with a bibliography and a good index.' *The Times Literary Supplement*

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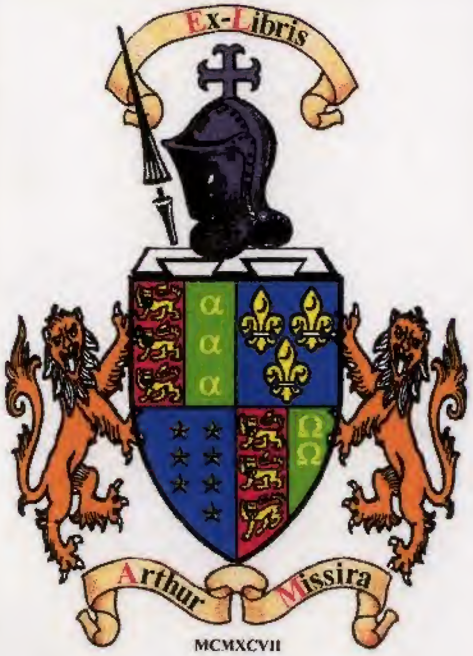

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THE SUN
Translated by J. B. Sidgwick

With Margherita Hack
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By
GIORGIO ABETTI

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Preface to this Edition

The English language edition of this book is based on the third Italian edition recently published by Boringhieri of Turin.

In recent years the advance of astronomical studies has been truly amazing and it is only with difficulty that we can keep up to date with it. This advance can be explained by great advances in the technical field, by the development of new theories, and in particular by the progress of astronautics and of radio astronomy which open new and wide horizons to astronomical observations and investigations.

As a consequence the interest of people in astronomy has increased, and so has the desire to learn more about the mysterious universe in circles outside those of professional and amateur astronomers.

The main purpose of this book is to give in simple and not too technical language, suitable for those who have not undertaken special studies in astronomy, a description of the most conspicuous objects of the sky, such as the stars and the planets.

A few centuries ago a transformation took place in astronomy. It was begun by Copernicus and continued by his successors. We can truly say that today we are witnessing the birth of a new astronomy, which perhaps in only a few years' time will enable us to increase enormously our knowledge of the heavenly bodies and of the universe which contains them. We must however humbly admit that the mystery of the cosmos is of such a nature and magnitude as to challenge man's understanding even when man has been successful in exploring by landings some very limited region of space. Considering the immensity of space in comparison with the shortness of the human life-span, we realize the utter impossibility of reaching remote parts of interstellar space, or even of approaching our Sun or some of the stars which populate the universe.

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In recent years it has been possible to improve the classification of the various types of stellar spectra, and now we begin to detect more clearly how the evolution of stars proceeds. This has been made possible by the use of large reflectors coupled with spectrographs and photoelectric devices.

The study of spectra has enabled astronomers to improve both the qualitative and quantitative analysis of the chemical composition of stars. It has enabled them to discover new physical characteristics such as the existence of intense magnetic fields and the effects due to the rotation and stability of some of the stars. At the same time theoretical studies have also progressed, so that we have now reached the stage when hypotheses and theoretical models can be suggested to explain the internal constitution and evolution of stars. Of course all this has been possible because we know today how the energy is generated which keeps the Sun and the stars alive.

In the case of the solar system we find that great progress has taken place in the technique of observations and that we have acquired a better understanding of the conditions prevailing on the planets. In this field there seems to be confirmation of the fact that life, as we understand it, namely in a form equal or similar to our own, is not present on the other planets of the solar system. Finally we have to take into account radio astronomy, the new branch of astronomy which with the reception of radio waves of various frequencies both from the stars and the planets, has opened a new extensive field of research. The fact that radio sources do not always coincide with stars presents us with new problems in a sky which is completely unfamiliar to us, a sky different from that which can be observed optically with our eyes or by photography.

Today however there is a greater promise of new discoveries with the advent of the stratoscope, the artificial satellite and the rocket. At last the dream of the astronomer is approaching its realization. He can obtain observations from regions well above the turbulent terrestrial atmosphere. With the stratoscope, which in reality is nothing more than a telescope attached to a balloon filled with helium, it has already been possible to obtain remarkable photographs of the Sun and of its spectrum, from heights outside the terrestrial atmosphere.

The artificial satellites and probes have already given exciting results. It would suffice here to mention the first photographs of the other side of the Moon and the wonderful journey of Mariner II, which has made such a contribution towards the knowledge of the

physical conditions of Venus. Until a satellite is able to penetrate the thick and persistent layer of clouds surrounding Venus, it will not be possible to learn more about the nature and conditions of its crust.

Since this book is intended mainly for the layman, only the names of the scientists who have contributed to particular problems are given without any detailed reference. This general reference together with the bibliography at the end of the book, should make it easy for anyone who is interested to consult the sources for further information. As far as the illustrations of this book are concerned, some are reproduced from the masterly articles of the late O. Struve, published in *Sky and Telescope* or from various astronomical periodicals, while some of the photographs were obtained from Mt. Wilson and Mt. Palomar.

Osservatorio di Arcetri-Firenze.
March 1965.

Preface to the First Edition

Research in science both in the practical and theoretical fields, is increasing rapidly in the modern world. This is partly due to the invention of new instruments and to improvements in the old ones and partly because new methods of research developed by the human mind in the field of mathematics can lead with success to the explanation and interpretation of the observed phenomena. Another reason is that exchanges and collaboration between scientists of many countries, when no exceptional circumstances prevent this, are nowadays so easy and so well organized that new results appear to follow each other almost continuously.

In astronomy it is difficult perhaps more than in other sciences to keep abreast with new ideas and to take stock of its new conquests. The reason for this is partly due to the fact that the number of scientists studying this subject is very limited and partly because of the immensity of the universe to be studied and the distance of the objects to be examined. The light emitted by these bodies is the only message which after having travelled through enormous distances, reaches us to tell us something of the universe in which the Earth moves, and this information until recently was very scanty. In recent times, however, great progress has been made in astronomy. Observations with instruments of ever-increasing power have led to many discoveries and extensive programmes of systematic investigations have led to a better understanding of the structure of those parts of the universe which are nearer to us. At the same time new theoretical speculations and hypotheses are being used as working instruments in order to increase our knowledge.

Stars and planets represent two classes of celestial objects which are very different from the point of view of physical conditions and distance, although the elements which form them are the same. The stars were known to the ancient dwellers of the Earth as 'fixed stars'

because they appeared to participate in the general motion of the celestial sphere, still maintaining the relative position to one another for periods of time comparable to that of human life. The 'wandering stars' of the ancients are the planets which were given this name because they could be seen to move quickly or slowly, among the 'fixed stars' in relatively short periods of time. As an example of the stars we can take the Sun, which is the only star so near to us as to present a disc with a considerable diameter which enables us not only to study the Sun as a whole but also in its various parts. The detailed study of the Sun by means of spectrographs having high dispersion has enabled astronomers to make discoveries and to obtain important results which could then be applied to the study of the stars in general.

The stars which shine with their own light are in some respect similar to our Sun. Among them there are many which have greater dimensions than the Sun, while others are of the same size or, in some cases, much smaller. We now know that they are gaseous spheres, and this knowledge was obtained only when the stars could be observed with the spectroscope. The planets, on the other hand, although composed of the same substances, are solid or liquid, surrounded by a gaseous atmosphere, and can be seen only because they are illuminated by the Sun.

In the interior of the stars an intense atomic life exists from a beginning to an end which are both unknown to us. This atomic life has an enormous and continuous flux of energy which to us seems inexhaustible. The planets, already cooled or in a stage of cooling, are in a condition to produce and develop forms of life. There is, therefore, a considerable difference between these two classes of celestial objects which we can study by means of the light they send us. Their physical conditions can be studied starting from a knowledge and an understanding of terrestrial phenomena in so far as analogies can be found and if necessary reproduced in a laboratory. Stars rule over the planets by means of their very great gravitational force and dictate their motion through space. Since planets are very small we can only see those belonging to the solar system, but this fact does not exclude the possibility that similar bodies exist in the neighbourhood of the many suns scattered in space. Stars and planets are but links in a chain which represents the life of the universe, a life that can be considered to have had a beginning and to have an end.

The evidence of what we see, confirmed by modern means of investigation adapted to the study of the sky, leads us to the con-

clusion of the existence of a stellar evolution, of which we are gradually discovering the various phases. It is true that the nebular hypothesis of Laplace has now undergone many modifications on account of the evidence obtained from modern investigations, but we can still admire the intuition of the great French mathematician, namely that the planets must be the children of the Sun and therefore must be made up of the same material. This was only proved many years after, when spectral analysis was applied to the study of the physical constitution of celestial bodies. There are today many indications that the stars are born from galaxies which exist in great numbers and which appear to us in various progressive stages of evolution.

Between galaxies and stars, the vast 'empty' space is occupied by gas and by atoms of elements well known on the Earth, so that we can formulate hypotheses about the condensation of matter through processes so far unknown to us. We are attempting, nowadays, to formulate hypotheses on the process of evolution from galaxies to stars and to planets. This process, although extremely slow when compared with the span of human life, is evident in celestial bodies in various phases or ages which seem to indicate a beginning and an end. In the case of the stars this can be observed in detail in various successive steps which can be easily interpreted with the help of atomic physics and of chemistry. For the galaxies we are still at the beginning of this type of investigation, because the distance of these objects is so great that the galaxies appear to be of very small dimensions and extremely faint. Finally as far as the planets are concerned, our knowledge is confined to the few which belong to the solar system, which, however, give us some indication of the physical conditions which can exist at various stages of evolution.

In the following pages we shall deal only with stars and planets. We shall try to describe how far astronomers have reached in the investigations of the physical constitution of celestial bodies, their position in the sky, their distance and their motions. A more detailed study shows a great variety among the stars, which at first would appear to differ only in their apparent brightness. Although as we have already stated, all stars are gaseous bodies, their temperature, their density and the constitution of their surface layers are very different. Different also are the systems of two or more stars, and star clusters which are bound together by the laws of universal gravitation.

The coloured lines, representing the spectra of the brighter stars,

which could be seen or photographed with difficulty some decades ago, are now replaced by high dispersion spectra, almost of the order of that obtained for the Sun, so that the spectral analysis of the stars leads us almost daily to a better knowledge of their nature and their characteristics. In the case of the majority of stars, these are definite, unchangeable, at least for periods of time longer than the average human life, but for the variable stars and novae they vary over short periods of time. It is therefore understandable how important it is to study and to follow these variations which, compared with the long life of the star, can be considered of extremely short duration. These variations will help to understand the transformation and evolution of celestial bodies. The spectroscope is also used to probe the atmosphere of the planets and enables us to decide whether the conditions are favourable for the existence of life. This, however, is a problem which still requires study.

This book has been written mainly with the intention of making known, outside the circle of astronomers, recent results obtained in the field where astronomy, physics, mathematics and chemistry are collaborating with such success. In the writing of this book several modern textbooks and periodicals well known to astronomers, have been consulted, and in particular the books by Schiaparelli, the excellent textbook on astronomy by Russell, Dugan and Stewart and the various volumes of the series *Harvard Observatory Monographs* and *Harvard Books on Astronomy* from which some of the illustrations have been taken.

I wish to express my sincere thanks to Mr. E. Thayaht for preparing some of the illustrations and to Professor A. Colacevich who has kindly collaborated in the revision of the text.

Osservatorio di Arcetri-Firenze.
August 1943.

Preface to the Second Edition

More than ten years have elapsed since the first edition of this book appeared. Ten years during which there has been intense work in all the observatories of the world with wonderful co-operation, as can be seen from the important reports of the last two general assemblies of the International Astronomical Union in Zurich (1948) and in Rome (1952). The results of the new observations and discoveries on one hand and the theoretical work on the other combine to give us an even greater knowledge of the universe. A knowledge which is still very limited when compared with the majesty and the infinite mysteries of the universe.

The general lay-out of this book is still the same as that of the first edition, but I have attempted to bring it up to date and to enlarge on many parts as a result of the work done during the last ten years. No doubt gaps will still exist because of the great amount of published material in these years. However I have tried to mention even if briefly the most important new developments, so as to inform the reader who, if interested, may follow this with a more specialized study of the subject.

In order to facilitate the reading of this book I have not given detailed bibliographical references, but I have limited myself to the mention only of the name of the scientists connected with the various investigations. This, together with the bibliography at the end of the book, should be sufficient to enable the reader to follow up any particular subject in which he may be interested. New illustrations have been added to the book; some obtained from the Mt. Wilson and Mt. Palomar observatories and others from the masterly articles by the late O. Struve, published in *Sky and Telescope* or other astronomical periodicals.

Preface to the Second Edition

I wish to express my sincere thanks to Mrs. M. Hack of the Merate Observatory and to Mr. M. Liguori of the Arcetri Observatory, for their help in the revision of the text.

Osservatorio di Arcetri-Firenze.
September 1956.

Part One

THE STARS

'And finally I ask you, foolish man, can your mind grasp that magnitude of the universe, which you consider to be too vast? If you can grasp it would you consider that your comprehension extends beyond that of the Divine Power? Do you mean to say that you can imagine greater things than those that God can create? But if you do not grasp it then why do you wish to give an opinion on things that you do not understand?'

Salviati in the Third Day of

Dialogues on the Two Chief Systems of the World

by GALILEO GALILEI (1632)

CHAPTER I

The Stars in the Sky — Apparent and Absolute Magnitude of the Stars

Mankind has always been impressed and moved by the spectacle of the starry sky on a moonless night, and perhaps even more so in ancient times than today, when our enjoyment of it is frequently spoilt by city lights and atmospheric pollution. The innumerable sources of light, of every gradation of brightness, are in some regions of the sky widely scattered; in others, they are crowded so closely that they give the impression of pale whitish clouds, as for instance in the Milky Way, which is a band of faint light that traces a great circle round the entire celestial sphere.

It was natural that, from the earliest times, observers of the heavens should have tried to group the stars into some sort of pattern. In this way their identification would be made easier in spite of the varying positions that they assume during the course of a single night as well as from season to season. Certain groupings of brighter stars immediately catch the eye, and these became known as the 'constellations'. The names given to them, whether suggested by their shape or indicating a desire to link the heavens with mythological heroes and supernatural legends and beliefs, have been handed down to us through the centuries. It is not known with certainty when constellations first originated. Their names are due to the Chaldeans in Mesopotamia, to the Egyptians and to the people of the Mediterranean countries including the Greeks. With the passing of time, star charts and celestial globes were made and in Bayer's *Uranometria* of 1603 we find forty-eight constellations described by their familiar names, the brightest stars being distinguished by letters of the Greek alphabet, followed by the genitive of the constellation's Latin name.

One of the earliest star catalogues was that of Hipparchus (150 B.C.), which gave, with fair accuracy, the positions of about a thousand stars. This was followed by others, which at first confined themselves to stars visible to the naked eye. With the invention of the telescope, successive catalogues listed ever increasing numbers of stars. Famous among these are the catalogue of the German astronomer Argelander (about 1850), containing more than 300,000 stars visible with medium-sized telescopes, the International Photographic Catalogue initiated in about 1890, with the co-operation of seventeen nations, for which a standard type of photographic telescope was used, and finally and most recently of all, the *Sky Atlas* compiled from photographs taken with the 48-inch Schmidt telescope at Mt. Palomar, which records practically every star accessible to the most powerful instruments in use today.

Man visualizes the infinity of space that surrounds the Earth as a dome which stretches above his head and is limited by the horizon. This illusion is most marked at night when the sky is studded with stars. But whereas celestial objects situated at the zenith are in imagination projected to what is in effect an infinitely great distance these same objects, when seen near the horizon, are unconsciously regarded as being nearer, and compared directly with terrestrial objects. This is the basis of the illusion that the Sun and Moon appear much larger when they are near the horizon than when they are high in the sky. A similar illusion extends to the constellations, so that when Ursa Major or Orion, for example, are just rising above the horizon, they appear to be disproportionately large, and become progressively smaller as they rise in the sky.

The stars are so distant that they appear as mere shining points, whether they are observed with the naked eye or with the largest telescope. That some appear to be much brighter than others depends on the fact that we receive a greater number of 'quanta' from them either because they are relatively near the solar system, or because they are intrinsically more luminous. Great intrinsic luminosity may arise either from the intensity with which they are radiating from every square inch of their surface, or from their relatively great volume.

All the stars visible to the naked eye and with the most powerful telescopes belong to the Galaxy, which is a system of finite extent. Within it, the Sun and its family of planets and their satellites move. These bodies, unlike the stars, do show measurable discs, either to the naked eye or with a telescope. Those of the Sun and Moon are

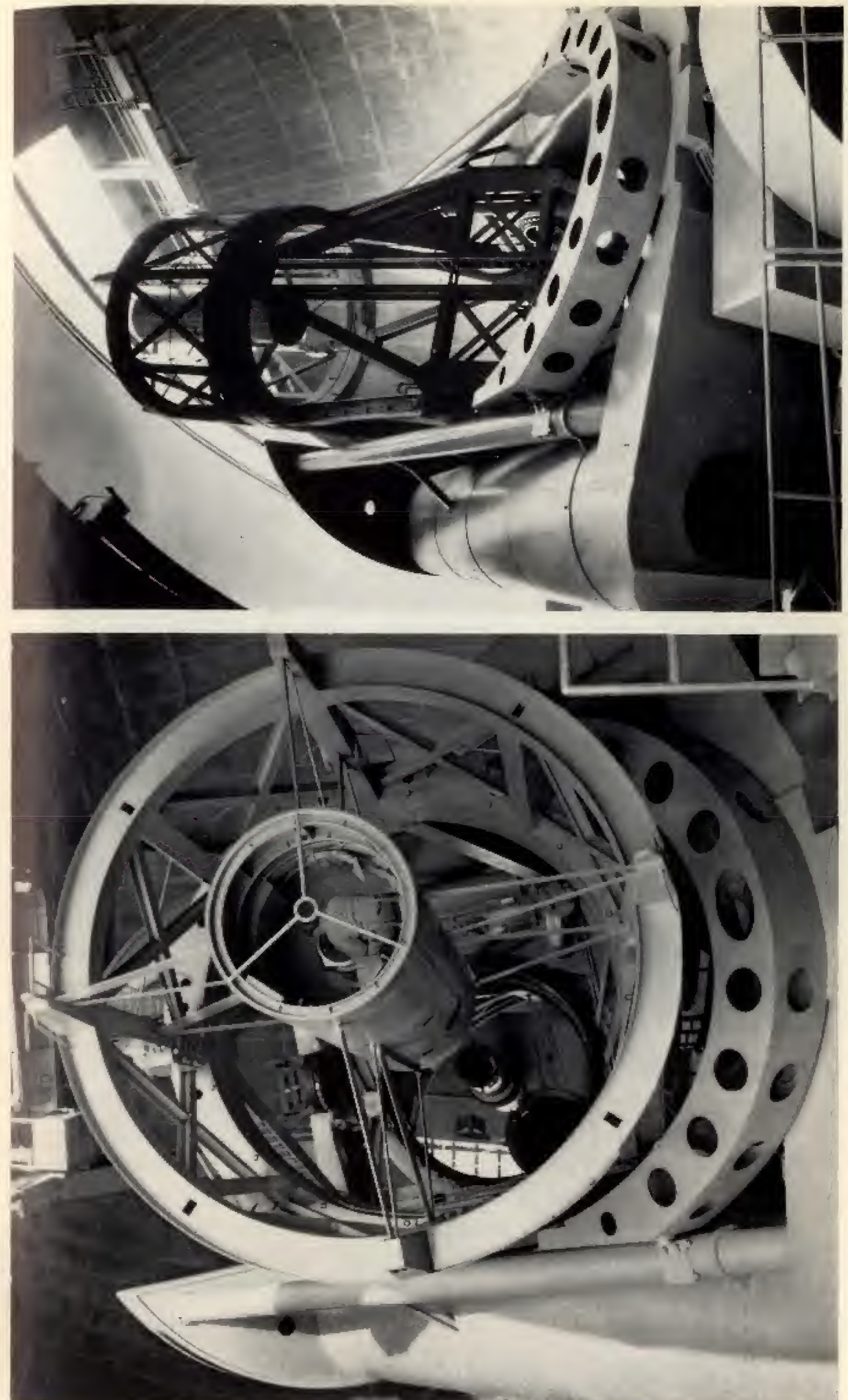


Plate 1. 200-inch Hale telescope Mt. Palomar showing (*left*) observer in prime focus cage, and reflecting surface of 200-inch mirror: (*right*) the telescope pointing to zenith; seen from the south

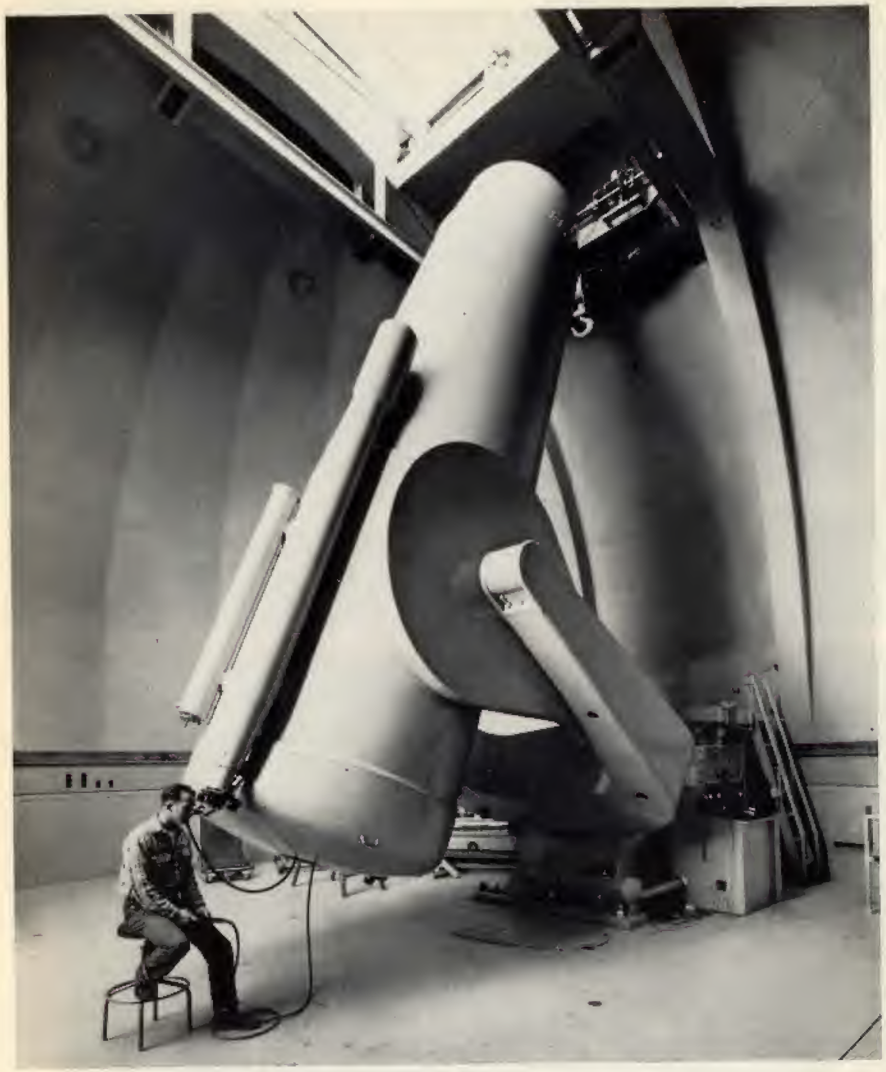


Plate 2. 48-inch Schmidt-type telescope, with observer at guiding eyepiece. Mt. Palomar

large and plainly visible while those of the planets and their satellites require a telescope to be seen. Images of finite size are also shown by the star systems lying outside the frontiers of our Galaxy, known as 'extragalactic nebulae' or simply 'galaxies', such as the Andromeda Nebula which is a system comparable to our Galaxy in size and shape.

In this book we shall be solely concerned with stars and planets, and consequently we shall be confining our attention to objects which belong to our own Galaxy. Also excluded from our survey is the cosmic matter both bright and dark, which is scattered throughout many regions of the Galaxy in the form of clouds of varying density and visibility.

The darkness of the background against which the stars appear to be projected varies from one region of the celestial sphere to another, and is also affected by the position of the observatory and the direction of the observation. The blackness of the night sky is, indeed, dependent on a number of factors, such as the observer's latitude, his height above sea-level, his distance from towns and cities and the existence, in the direction of observation, of the cosmic matter mentioned above. This may consist either of star clouds or of nebulous matter bright or dark, and the stars may be observed either projected against it or embedded in it. The luminous points do not normally appear to shine steadily, but to twinkle to a greater or lesser extent. The degree of this scintillation depends on the state of the atmosphere, and therefore on the meteorological conditions obtaining at the time of observation.

This effect of stellar scintillation is in fact produced by variations of the refractive index in different regions of the Earth's atmosphere and by the rotation of the Earth.

Astronomers have for these reasons been led to search for localities which provide the ideal conditions of clear skies and steady star images, conditions which are seldom realized, and then only in a few regions of the Earth's surface. Altitude above sea-level is one of the most important factors since it raises the observer above the lowest levels of the troposphere, which are both the most turbulent and also the most affected by industrial pollution. A number of observatories have therefore been established on mountain summits. A mountain site, however, especially if it is precipitous and barren of vegetation, suffers from the drawback that convection currents form around it, and these have an adverse effect on the steadiness of telescopic images. Uplands and plateaux covered with vegetation

and having the maximum number of cloudless nights a year, are therefore to be preferred. In the United States, for example, lengthy investigations indicated that the requisite conditions were to be found at Mt. Palomar (California), and it was there that the 200-inch reflector was sited. Another region with a high incidence of clear skies combined with the atmospheric stability required for astronomical observations has been found in South Africa and here several observatories have been established in recent years for the study of the southern celestial hemisphere which, up to the present time, has been comparatively neglected.

Because of their great distances, the fixed stars appear, even through the largest telescopes currently available, as bright points. Each is surrounded by a number of diffraction rings, and the linear diameter of the whole image is a function of the focal length and aperture of the objective. Since the time of Galileo and Newton, telescopes used in astronomy have been of two types, refractors and reflectors; the former employ lenses and the latter mirrors. An interesting struggle for supremacy ensued between these two types. At first it appeared that the refractor was superior because its objective does not deteriorate with the passage of time, and the instrument is easier and more convenient to use. The metal mirrors (speculum) originally used for reflectors oxidized rapidly, and the silver films of the glass mirrors that later replaced them likewise had to be renewed frequently. Furthermore, the observing position is inconveniently placed in the Newtonian form of the instrument, at the upper end of the tube. But eventually a limit was reached to the size of the object glasses that could be manufactured, owing to the difficulty of casting homogeneous glass blocks larger than about three feet in diameter without internal strains developing. It was also increasingly difficult to meet the requirements of photography which are more demanding than those of visual observation, as far as the correction of the dispersion of the light passing through the lens is concerned. Mirrors, on the other hand, can be manufactured from glass discs which do not have to be perfectly homogeneous. This, together with the development of more convenient forms of the reflector than the original Newtonian combination, the Cassegrain for instance, put the reflector decisively in the lead, at any rate from the point of view of size. Ever larger blocks of glass were manufactured successfully, culminating in the 200-inch disc (Plate 1). Since ordinary optical glass is excessively sensitive to temperature changes, which result in distortion of its images, Pyrex has been widely used in recent years.

This consists largely of quartz which is not noticeably affected by changes of temperature. Furthermore, silver films have now been superseded by aluminium which is deposited on the mirror's surface by electrical means, in the form of an extremely thin film. Although the process is by no means new, it is only recently that it has been applied to astronomical instruments and it is currently being put to an increasing number of uses.

The mirror to be aluminized is thoroughly cleaned and is then enclosed in a chamber which can be evacuated almost completely, and which contains a number of wolfram elements round which pure aluminium wire has been wound. The aluminium is evaporated by means of an intense electrical discharge and is deposited on the surface of the mirror. An aluminized mirror has two important advantages over a silvered one. In the first place, the reflecting surface is extremely tough, and therefore does not deteriorate easily; it can be washed with soap and water, which is impossible in the case of a silvered mirror. Secondly, the reflectivity of the aluminium surface, although very similar to that of the silver film for visible wavelengths, namely in the region of the spectrum between violet and red, is considerably greater in the violet. Furthermore, the silver film is completely transparent to ultraviolet radiation, whilst the aluminium film reflects a very high percentage of it, a fact of great importance in the study of stellar spectra.

The ordinary astronomical telescope is only capable of providing perfectly corrected images on its optical axis, and for this reason its usable visual field is very restricted. Observing with one of Galileo's original telescopes, it is always a matter for wonder that he was able to make so many discoveries with so limited a field. As, gradually, photography replaced visual observation to a very large extent, the necessity and the possibility of using ordinary photographic objectives for astronomical work led to rapid progress in this direction. Since parallel developments were taking place in photographic processes, it was not long before compound objectives consisting of four, six or more lenses were being constructed. These were adapted to celestial photography, and covered fields far exceeding the few minutes of arc of the ordinary visual telescopes. The superb photographs obtainable today cover areas of 20° or even 30° and make us wonder whether, in this field at least, the refractor has not completely surpassed the reflector.

Possibly the most satisfactory instrument is actually a combination of the reflector and the refractor. In 1930 it occurred to Bernhard

Schmidt, an optician of the Bergedorf Observatory at Hamburg, to combine a mirror and a lens, more accurately we should say a correcting plate, which provided a happy and practical solution of the problem of corrected field. Its performance was comparable with that of the best photographic objectives, while surpassing them in size as the parabolic mirror had surpassed the object glass.

The Schmidt telescope consists of a spherical mirror working in combination with a correcting plate located at its centre of curvature (fig. 1). A spherical mirror is incapable of bringing the parallel rays

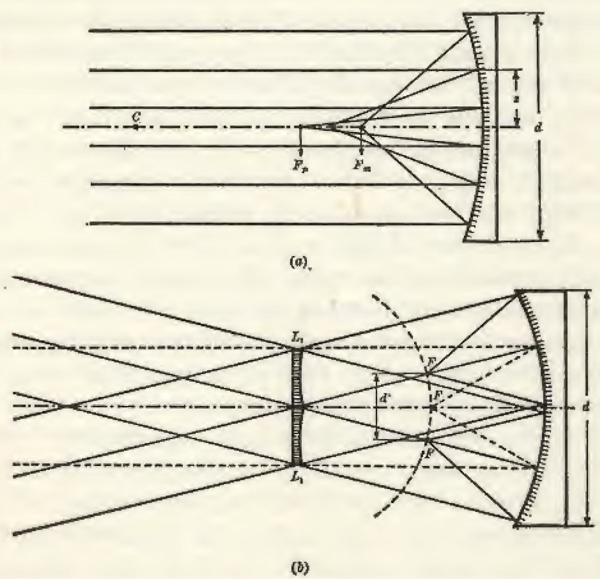


FIG. 1. Spherical mirror. (a) F_p and F_n are two foci of a spherical mirror. (b) Schmidt system. Spherical mirror and correcting plate.

from a star to a single focus. Those falling on the periphery of the mirror are reflected to a focus nearer to the mirror than those reflected from its central region. The images are therefore not sharply defined, and it is for this reason that parabolic mirrors had to be used. The sole function of the interposed correcting plate is to bring all the rays to the same focus. This it does by deviating slightly the rays that arrive near the centre of the mirror, while bending those of the peripheral zone slightly outwards, so that they strike the mirror at varying angles and thus are all brought to the same focus. The correcting plate is usually plane on one side and the complex

curve of the other surface is calculated mathematically. It is very thin, and its curvature is so small that it is not perceptible to the naked eye, but only by optical tests. With such a correcting plate, the image of a star near the mirror's axis is thus as well defined as one produced by a parabolic reflector, but the great additional advantage of the new system is that by virtue of its geometrical properties it provides images of stars lying several degrees from the optical axis, which are as well defined as those at the centre of the field. The field is therefore of the same order of size as that of photographic objectives, which are nowadays being replaced by the Schmidt telescope because of its freedom from residual chromatic aberration, because of the large apertures which can be attained, and because of the ratio between its focal length and aperture, which may be made as small as unity, thus making the instrument photographically very fast. In this way it is possible to construct instruments of great or small focal length, corresponding to small or large fields, for different types of astronomical work, according as to whether it is desired to study the stars individually or in large numbers simultaneously (Plate 2).

Another important factor in the use of telescopes is their *resolving power*, both theoretical and practical. The two components of a double star can just be seen individually if the centre of the diffraction pattern of one falls on the first dark ring of the other's–it being assumed that the two stars are of equal magnitude. It can be calculated that the resolving power of a telescope is about $0{\cdot}6\ \lambda/R$, where λ represents the mean wavelength of the radiation from the star, and R represents the radius of the object glass or mirror. Hence the theoretical resolving power of an objective 4 inches in diameter, for light within the visible range, is about 1″, and for a 40-inch objective about 0·1″. These conditions are important, whether for determining the quality of a particular instrument, or for indicating the possibility of separating, and clearly seeing, celestial objects which are very close to one another, as in the case of double stars.

The photographic plate used in conjunction with a telescope should, like the eye, show the stars as well defined points only differing from one another in size because of their apparent magnitude, that is to say the number of quanta reaching us from each star. In practice, the photographic plate records a dark point the diameter of which depends on the brightness of the star. It must be realized, however, that the apparent diameter of a star depends solely on the number of grains in the emulsion that have been affected, over a

greater or smaller area of the plate, and has nothing whatever to do with the real diameter of the star, as it is in the case of a planet. It follows from this that the light grasp of a telescope of given aperture is determined solely by its capacity to collect a large quantity of light and thus to reach stars which are too faint to be seen with the naked eye.

Once a scale of magnitude for the stars is defined, it is possible to express by numbers which star can be seen with the eye either unaided or aided by telescopes of various sizes or by the photographic plate which has the advantage of being able to accumulate the radiation throughout the whole period of the exposure. The earliest empirical classifications by Hipparchus and Ptolemy, based on the sensitivity of the human eye and its ability to distinguish between stars of various intensities of brightness, comprised six magnitudes. The first magnitude included about twenty of the brightest stars, while the sixth was composed of the faintest stars visible to the unaided eye. This classification became ever more extended, more especially after the invention of the telescope, which widened so much the scope of stellar observation, making it necessary to establish a precise basis for the scale of magnitudes gradually determined by different types of photometers with ever-increasing accuracy.

Since the ratio between the intensity of the light received from two stars of consecutive magnitudes is very close to the fifth root of 100, namely 2·512, the logarithm of which is 0·4, this latter has been chosen as the unit of stellar magnitudes. Thus if I_m represents the apparent intensity of the radiation received from a star of magnitude m and I_n that of one of magnitude n, we have in general:

$$\frac{I_n}{I_m} = (2{\cdot}512)^{m-n}$$

or, taking the logarithms,

$$\log \frac{I_n}{I_m} = 0{\cdot}4\,(m-n)$$

by means of which expression we can derive the magnitude from the intensity and vice versa. If I_o is the intensity of a star of magnitude 0, we have:

$$\log \frac{I_m}{I_o} = -0{\cdot}4\,m$$

If we put the intensity of a star of magnitude 0 such as Vega

(α Lyrae) equal to unity, we can calculate the intensities of successive magnitudes. It will be found, for example, that 100 stars of the fifth magnitude, or 3981 of the ninth, will be required to provide the same amount of light as one star of magnitude 0.

Negative values of the same scale are used for the few stars brighter than Vega, for the planets, for the Sun and for the Moon. Thus, always using the same inter-magnitude relationship, the magnitude of Sirius is $-1{\cdot}6$, Venus about -4, the full Moon $-12{\cdot}5$, and the Sun $-26{\cdot}7$. Comparing these values with those of terrestrial light sources, the magnitude of a standard candle at a distance of one yard is $-14{\cdot}4$, and at a distance of one mile, $+1{\cdot}8$.

As has been said, the unaided eye can reach to magnitude 6. It will be interesting to note here the progress made by increasing the telescopic power. The light grasp of a telescope is proportional to the area of its objective, which in turn varies as the square of its diameter. In order to reach one magnitude fainter, therefore, we must increase the aperture in the proportion of the square root of 2·512, namely 1·6 to 1. Increasing the aperture of a telescope ten times would theoretically bring about five more magnitudes within its reach. A telescope with an aperture of one inch, like that used by Galileo, should reach to magnitude 9, an aperture of 16 inches to magnitude 15, of 40 inches to magnitude 17, and of 100 inches, such as the Mt. Wilson reflector, to magnitude 19. It can be seen how slowly the gain of magnitude increases with increasing size of the instrument; this gain, however, although it may appear small, is in fact very considerable, since it opens up ever vaster regions of the universe.

In order to reach stars so faint that they are beyond even the Mt. Palomar reflector, very promising experiments have been carried out with photoelectron telescopes. The advantage of the photoelectric instrument over the photographic plate is that it reveals images whatever their intensity, while the photographic emulsion is barely sensitive to faint objects. Modern photocells and photomultipliers show that no sensitivity threshold exists for the photoelectric effect as it does for the photographic plate. This enables us to convert photons into electrons, and the latter, with the help of electron optics, can be used with a considerable reduction in the time of exposure.

The electron telescope is based on the same principles as the electron microscope. It consists essentially of a photocathode upon which impinges the image which is to be photographed. The optics of the instrument consist of electrostatic lenses and of a magnetic

lens which enables the electron image to be focused upon the electron sensitive plate.

Lallemand of the Paris Observatory, who for several years has been carrying out investigations in this field, has obtained some remarkable 'electron' images of celestial objects with exposure times far below those required by direct photography and of a far greater quality, having very little fog and excellent contrast. Moreover the very short exposures required, eliminate the troublesome effects due to atmospheric turbulence.

The above description of the scale of magnitudes concerns visual magnitudes, that is to say those determined by direct visual observation with a telescope. But the eye is only sensitive to a limited region of the spectrum, lying between the violet and the red. Radiating bodies, such as the luminous spheres of gas which we call stars, emit radiations the wavelengths of which extend over a far wider range than that to which the eye is sensitive. This has been discovered and investigated as appropriate instruments have, one after another, been invented and perfected.

The earliest astronomical photometer was the human eye, used sometimes with the aid of a telescope, to determine the difference of magnitude between stars. Later, various types of photometers were invented, based on different principles, but in every case used visually. The instrumental basis of modern stellar photometry is provided by the photographic emulsion and the photoelectric tube. Such instruments can explore either a wide range of wavelengths, from the ultraviolet to the infrared, or a restricted and well-defined group of wavelengths.

The stellar magnitudes of which we have been speaking are known as 'apparent magnitudes' since they depend not only on the actual luminosity of the star but also on its distance from the solar system. Since the apparent magnitude of a star is known to vary inversely to the square of its distance, we can derive either of these quantities, distance or intrinsic luminosity, as soon as one or the other is known. Modern methods of determining either or both of these data will be described later.

The study of the physical constitution of the stars, as well as of the structure of the universe, demands that we should be able to make direct comparisons between the absolute luminosity of various stars, independently of their distance. To enable us to do this, astronomers make use of the concept of 'absolute magnitude'. The absolute magnitude of a star is the magnitude, measured on the same

scale as that adopted for apparent magnitudes, that it would have if the star could be transported to a standard distance from the solar system. Since the astronomical unit (A.U.), that is the mean distance from the Earth to the Sun, is too small for this purpose, the International Astronomical Union has adopted the distance of 10 parsecs, which is equal to 32·6 light-years. A parsec is the distance from which the radius of the Earth's orbit is seen under an angle of 1 second of arc. The absolute magnitude of the Sun, the apparent magnitude of which is −26·7, becomes 4·8, that is to say at a distance of 10 parsecs it would still be easily visible to the naked eye. Sirius, at a distance from the solar system of about 9 light-years, and which has an apparent magnitude of −1·6, has an absolute magnitude of 1·3; its intrinsic luminosity is thus 27 times that of the Sun. Antares (α Scorpii), at a distance of about 360 light-years, if brought to a distance of only 32·6 light-years, would change from an apparent magnitude of 1·2 to an absolute magnitude of −4·0; it would equal Venus at its brightest, and is a star 3,500 times more luminous than the Sun. One of the brightest stars in the Galaxy is Rigel (β Orionis), which with an apparent magnitude of 0·3 and a distance of 470 light-years, has an absolute magnitude of −5·5: it is thus 14,000 times as bright as the Sun.

CHAPTER II

The Colour of the Stars — Stellar Photometry

To determine the apparent magnitudes of the stars more accurately than is possible by simple visual observation, various types of visual photometers have been developed. One of these, the wedge photometer, employs a glass wedge to weaken the intensity of the stellar image to the point of extinction or until it is equal to that of a standard source of light in the telescopic field. The absorption of the light passing through the wedge increases steadily from its apex to its base. In another type of photometer the intensity of the unknown star is reduced, so that it can be compared with a known one, either natural or artificial, by means of a system of polarizers, such as Nicol prisms. With these and similar photometers, an enormous number of stellar images have been measured, from the brightest in the sky down to those that are invisible to the naked eye. Such work was the basis of the visual photometric star catalogues, and with good measurements, corrected for the effects of atmospheric absorption, an accuracy of one-hundredth of a magnitude may be attained.

Photography offers another means of measuring the apparent brightness of the stars. In the early days, use was made of the fact that the diameter of the photographic image of a star is proportional to its brightness, but this method did not produce results of a satisfactory accuracy. A better method was to measure the degree of darkening of the patch of emulsion that had been affected by the quanta received from the star. This image-density is a logarithmic function of the star's brightness and of the exposure time. In practice, the measurements of intensity are not quite as simple to make as this statement might imply, since the density of the photographic image is also affected by the state of the sky, the quality of the

emulsion, and the development. When making these measurements, which nowadays have attained a high degree of precision, each plate is calibrated photometrically by one or other of several methods. In this way its density curve is determined in terms of a scale of known density gradations, or of diffraction images produced by a grating, or again, of a series of stars of known magnitudes, such as the Polar Sequence.

The density of photographic images is measured with an instrument known as a microphotometer. In one form, this instrument allows the image in question to be compared with another of known density. Alternatively, the eye may be dispensed with altogether, and its place taken by a thermocouple. This will produce a greater or smaller deviation of a galvanometer needle according as to whether the image transmits more or less light to it. Once the density curve has been established, the brightness of the star can be deduced from the density of its image. This method has been greatly developed in recent years. It is obvious that with long exposures and powerful telescopes it enables us to reach magnitude levels not attainable by purely visual methods.

The 'photographic magnitudes' that were determined with emulsions available in the early days of photography were notably different from those derived visually. These emulsions were in fact sensitive to violet radiations in a region in the neighbourhood of a wavelength of 4000 Å, while the eye is most sensitive to the green-yellow radiations with a wavelength of around 5500 Å. But the stars are of various colours, as can be clearly seen in the case of the brighter ones, and since the emulsion is particularly sensitive to blue light, the image density of a blue star will indicate a greater brightness than that derived by direct visual comparison. Conversely, a red star will appear to be brighter visually than photographically, since the emulsion is affected very slightly, if at all, by its light. Thus it is necessary to make a distinction between the photographic and visual magnitudes of a star. A comparison of the two leads to the concept of *colour index*, which, as the name suggests, is a measure of the star's colour. If we define the colour index as the difference $m_p - m_v$ and fix the zero point of the colour index scale at the blue-white stars, then the colour index of a red star will be positive, and that of a blue star negative.

In the course of time considerable progress was made in photographic technology. Emulsions were developed which were sensitive, first to yellow light (orthochromatic), then to red (panchromatic)

and the term colour index as defined above, ceases to have any meaning. Modern photographic emulsions are in fact sensitive to a much wider range of wavelength than the eye, and therefore when we speak of photographic magnitude we must specify to what 'effective' wavelength we are referring, according to the type of emulsion, and the coloured filter used. By a suitable choice of emulsion and filter it is possible to obtain photographic measurements of stellar magnitudes which are identical with those obtained visually; 'photovisual magnitudes' as they are called.

A fairly recent type of photometer employs a photoelectric cell to measure the intensity of the various radiations emitted by the stars. When certain metals, such as sodium and potassium, are exposed to light in a vessel containing only rarefied argon or helium, the number of electrons that they emit is directly proportional to the intensity of the incident light; hence if the extrafocal telescopic image of a star is formed on a cell of this type, its brightness can be measured by means of an electrometer. Magnitudes determined in this way are also dependent on the wavelength sensitivity of the cell, which varies according to the metal used for the photoelectric element.

Photoelectric photometry has made great strides in recent years, thanks to the development of the photomultiplier, the great advantage of which is that it does itself amplify the weak primary current set up by the electrons liberated by the quanta emitted by the star and collected by the telescope. With an ordinary photocell, the current generated by even the brightest stars is only about one thousandth of a microampere. In this lies the chief limitation of the method. The choice of suitable stars is restricted to those that are bright enough to set up a sufficiently strong current to be measurable by a galvanometer.

On the other hand with the photomultipliers currently available, the brightness of relatively faint stars can be measured with great precision even with medium-sized telescopes. With a 7-inch refractor, for instance, the photomultiplier will collect about 10^{-13} watt from a star of the sixth magnitude. The output current, after nine stages of amplification, will be 5×10^{-8} amp. which can easily be detected by a galvanometer or recorded after suitable amplification. Such an instrument is capable of measuring the brightness of stars down to magnitude 11. Its accuracy, in the case of the brighter stars, is of the order of a few thousandths of a magnitude.

The invisible heat radiation of the stars also repays investigation.

The instrument used for such work, mounted at the focus of a telescope, is known as a thermocouple. It is sensitive to all wavelengths, but in particular to those infrared variations which we experience as heat. Were it not for the selective absorption exercised by the Earth's atmosphere, a thermocouple would be able to measure the total radiation reaching us from any given star. Stellar magnitudes, as determined with a thermocouple, are known as 'bolometric magnitudes'. The difference between the visual magnitude and the bolometric magnitude is called the 'bolometric correction'. It is arbitrarily adjusted to be zero for stars near the temperature of the Sun.

The quantity of heat that we receive from the stars is exceedingly small. For example, the total radiation of Betelgeuse (α Orionis), a red star of the first magnitude, when at the zenith, is $5{\cdot}4 \times 10^{-12}$ watts per square centimetre, which is equivalent to $7{\cdot}7 \times 10^{-11}$ calories per minute per square centimetre. Sirius, a blue star which visually is ten times brighter than Betelgeuse, emits only 75% of the total energy emitted by it. It will be appreciated from these figures how extremely sensitive a thermocouple must be in order to measure such microscopic quantities of heat energy, and that it must be used in conjunction with the most powerful telescopes.

The observers of ancient times had attempted, even without the aid of telescopes, to chart the heavens and to record the magnitude, estimated visually, of each star, as was done by Ptolemy and other early compilers of star catalogues. Coming nearer to our own times, since the invention of the telescope, the two Herschels recorded the visual magnitudes of the objects in both hemispheres that figured in their catalogues; Argelander's catalogue, similarly, quoted visual magnitudes. With the introduction of photometers, a complete catalogue, *Durchmusterung*, of the northern hemisphere giving the magnitudes and colours of all stars down to magnitude 7·5 was undertaken at Potsdam Observatory. The photometer used was a Zöllner polarizing photometer having an artificial star for comparison. The colours of the stars were expressed in terms of a scale from white to red.

One of the pioneers of astronomical photometry was Pickering, who, at the Harvard College Observatory, initiated and completed a vast programme of observations of stellar magnitudes and spectra. For the former, he and his colleagues made use of a polarizing photometer by means of which each star was compared with Polaris. Pickering's first *Harvard Catalogue* was followed by the *Henry Draper Catalogue*, in which are recorded the magnitude of more than 220,000

stars in both hemispheres, as well as their spectroscopic classes which we shall discuss later. This monumental undertaking has made available to astronomers a mass of accurate stellar data which, already, has produced results of the first importance in connection with the structure of the Galaxy.

The use of photometers became increasingly general, not only for the determination of large numbers of stellar magnitudes, but also for the discovery and investigation of individual stars of variable brightness, hence known as variables. As an increasingly wide variety of methods became available, the necessity arose of being able to compare the results obtained at different observatories and with different instruments. To this end, the *Polar Sequence* of stars was established. This consists of a large number of stars, both bright and faint, whose magnitudes had been determined by a variety of photometric and photographic methods. The accuracy of these determinations is the greatest attainable with existing instruments, and the *Polar Sequence* is universally accepted as a fundamental standard of stellar magnitudes from the second to the twentieth.

Many measurements of magnitudes have been made by means of photoelectric photometers not only in the *Polar Sequence* but also in 'selected areas' where new 'sequences' have been established which, for the purpose of comparison and calibration, are as good as the *Polar Sequence*.

It will be apparent from even this brief survey of astronomical photometry that, with the continual improvement of the instruments employed and the greater accuracy of the measurements made, it is necessary to specify whether a magnitude or brightness of a given star refers to its total radiation (bolometric magnitude) or only to a certain radiation. The detailed study of these radiations will obviously be facilitated if we know the star's spectrum, for this will tell us the intensity of its radiation at different wavelengths. Nevertheless, even the total brightness of a star is an invaluable datum, and the only one we have in the case of stars that are too faint for their spectra to be photographed with existing equipment.

Modern astrophysics tends to concentrate on the measurement of magnitude and colour as a function of wavelength, that is to say for precisely defined regions of the spectrum which can be isolated with ever-increasing precision by the appropriate choice of instruments, photographic emulsions and filters.

This choice is much facilitated nowadays by the wide range of filters that are available. These may be either of the ordinary type,

or of the interference type which isolate very narrow regions of the spectrum. When these are used in conjunction with photographic plates having a sensitivity which is appropriate to the spectral region that is to be investigated, the derived colour index refers to a precisely determined effective wavelength and can conveniently be used, in the case of faint stars, to give us the information normally obtained from the spectrum.

CHAPTER III

Stellar Spectra — Their Investigation and Classification

Wollaston, in 1802, made the discovery that the spectrum of the Sun is not really a continuous band of colour from violet to red, but is interrupted by a number of apparently dark lines. Some years later, Fraunhofer, using an improved form of instrument, showed that these lines, of varying intensities, number several thousand. The subsequent investigations of Herschel, Kirchhoff and Bunsen began to establish the correspondence between these dark absorption lines in the spectra of the heavenly bodies and the bright emission lines of spectra produced in the laboratory. From that time spectroscopic analysis became a powerful weapon in the hands of the astrophysicist, enabling him to determine the chemical composition of the stars and proving incontestably that the whole universe is constructed of the same elements that we encounter on the Earth.

A few decades later, Donati, Father Secchi and Huggins, using extremely simple equipment, consisting either of a prism mounted in front of the object glass of a telescope, or of a simple spectroscope mounted at the eye-piece end, initiated a systematic study of stellar spectra. These minute coloured bands are crossed by Fraunhofer lines, and the laborious work of these early investigators consisted in the measurement of the positions and intensities of these lines. But here again, photography soon came to the aid of the visual observer, and in conjunction with more powerful telescopes and high dispersion prism or grating spectroscopes it soon began to yield an ever richer harvest of important results.

There are today many different types of spectroscopes and spectrographs, the latter being the name given to the instrument when it is used exclusively photographically, as is the normal practice. Various

Plate 3. 49-inch reflector of the Asiago Observatory (Italy). The spectrograph is attached to the reflector used as a Cassegrain

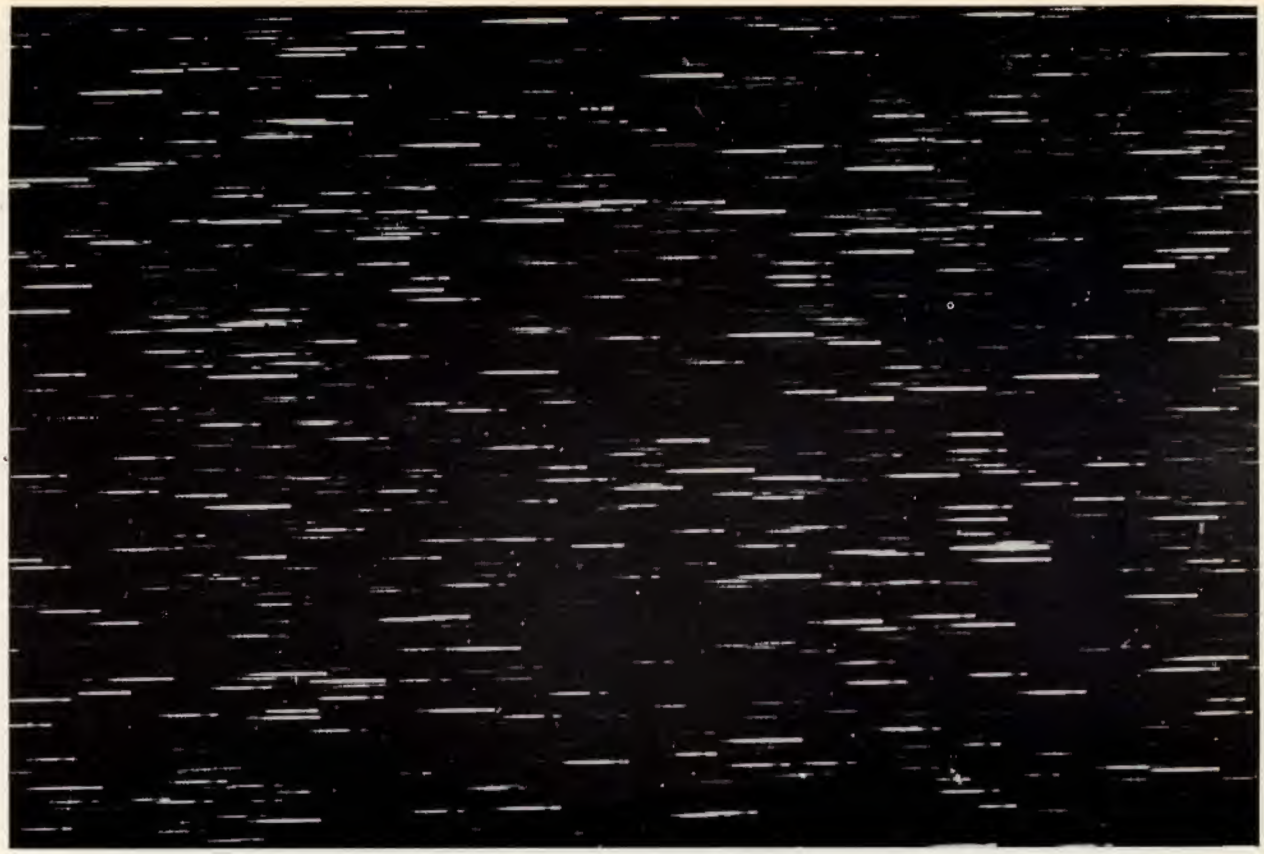
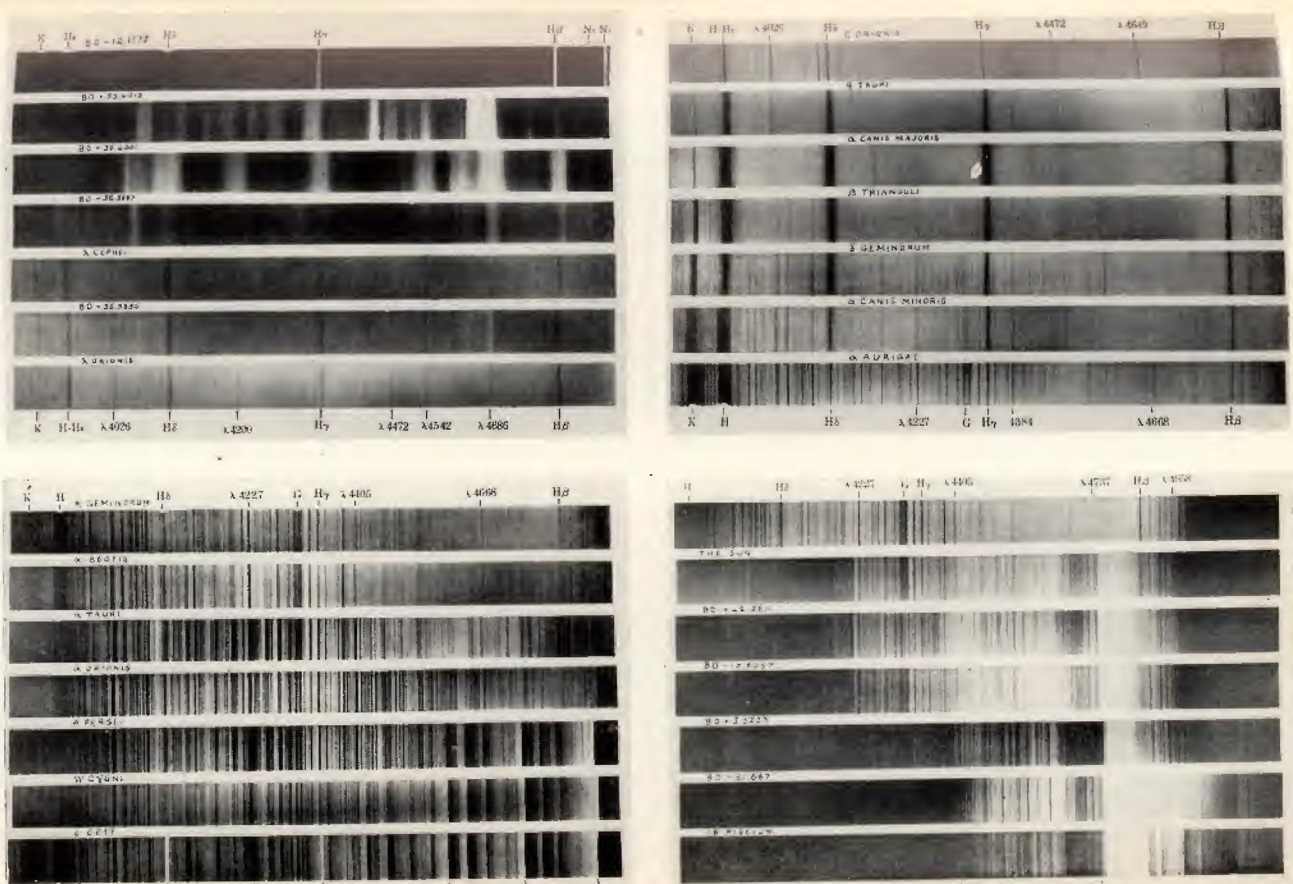


Plate 4. Region of the sky photographed with an objective prism



(a) (b) (c) (d)

Plate 5. Typical stellar spectra (a) Class Pa and O, (b) Class Bo to Class Go (c) Class G5 to Class Md (d) Classes G, R and N

combinations of lenses and mirrors are used, in conjunction with one or more prisms or with diffraction gratings (Plate 3 and fig. 2). Spectrographs designed specially for the observation of the Sun are much more varied in form than those for the study of stellar spectra, since the great brightness of the Sun allows the use of long focal lengths and of gratings which distribute the available light into spectra of different orders, and are therefore, usually, less bright than those produced by prisms.

Diffraction gratings were brought to a high degree of perfection by Rowland, who also thought of engraving them on a parabolic surface in order to eliminate any other optical parts, particularly when studying the solar spectrum. By these means he was able to photograph the solar spectrum on a very large scale. From the red to the violet it measured 42 feet, and revealed a total of 20,000 Fraunhofer lines. Owing to the practical difficulties of attaching long spectrographs to the eye-piece end of movable telescopes, the stationary horizontal or vertical telescope was developed for solar observations. A telescope of the latter type, known as a solar tower, was first built by Hale. The spectrographic part of the instrument is housed below the tower in a pit, aligned on the axis of the tower. This makes it possible for very large focal lengths to be used and for the spectrograph to be mounted in a place which can easily be maintained at a constant temperature. Large-scale photographs of the spectrum of the Sun, such as those taken by Rowland, are obtained with such instruments, and as we shall see, these permit the detailed investigation of the Sun's physical characteristics.

In recent times, fixed spectrographs have been employed in combination with reflectors of large aperture. These do not follow the diurnal motion of the telescope, but remain stationary and are mounted at the base of the telescope. In order to use these instruments, the light from a star, gathered by the main mirror of the telescope, is directed, by suitably arranged secondary mirrors, to the lower end of the polar axis of the instrument, where the image is formed on the slit of the spectrograph. The optical parts of the spectrograph in the case of modern instruments such as those used with the 100-inch and 200-inch reflectors at Mt. Wilson and Mt. Palomar, consist of Schmidt-type cameras and a Pyrex diffraction grating ruled with about 15,000 lines per inch. A combination of this kind is capable of giving on the plate a spectrum which is 17 inches long, all in focus, with a dispersion of 3 Å/mm. This is comparable with the spectra obtained with solar towers. With a dispersion of this

magnitude, it is possible to study the spectra of only the brightest stars. To obtain spectra of fainter stars it is necessary to use one or more prisms according to the dispersion required and the quantity of light available. Cameras of various focal length are often used to record the spectra on large or small scale, the amount of light available being an important factor.

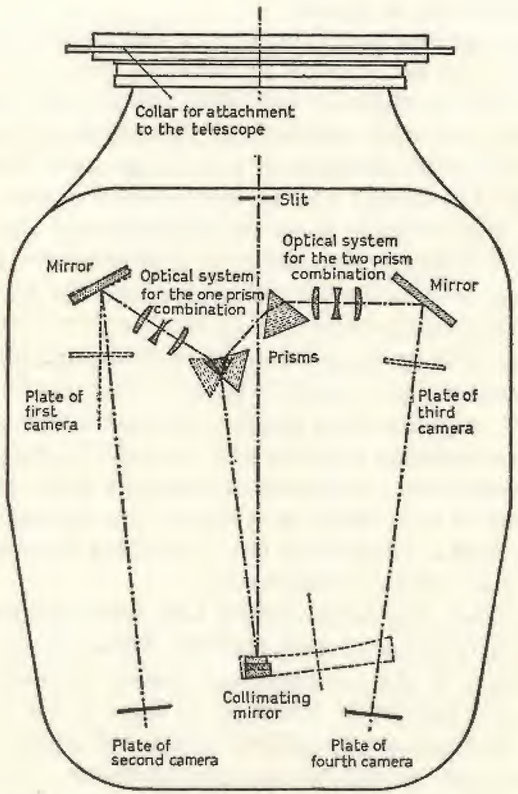


FIG. 2. The spectrograph of the Asiago Observatory.

In order to give some idea of the amount of light lost in the optical train of these instruments, it will suffice to say that an equipment consisting of a spectrograph employing a 63° prism, a camera giving a plate scale of about 40 Å/mm. and a reflector of 60 inches aperture, will require an exposure of one hour to record the spectrum of a sixth magnitude star. It is common practice to project the image of

a luminous terrestrial source into the slit so that the emission spectrum of this source is recorded together with that of the star. The luminous source can be the arc or spark of, for example, iron or an electric discharge in a rarefied gas such as hydrogen. In this way an accurate comparison of the wavelengths of the lines in the two spectra can be made.

When, on the other hand, a large number of spectra have to be recorded, for statistical or for stellar classification purposes, or when we want to reach the faintest stars accessible to the instrument, an objective prism is used. This is a prism with a circular base which is mounted in front of either the telescope objective or mirror. With a photographically corrected object glass, or a Schmidt system, it is possible to record a wide expanse of sky, and the spectra of all the stars in it, down to the limit imposed by the light-grasp of the instrument (Plate 4). Prisms of this type normally have a small refracting angle, and hence the dispersion of the spectra is small, though it is adequate for purposes of classification and for other investigations which do not demand a comparison spectrum for each stellar spectrum.

The electron telescope will be a great asset in conjunction with slit spectrographs, in obtaining spectra of stars and galaxies which are so faint that they cannot be studied with the ordinary optical telescopes available. The experiments recently carried out by Lallemand at the Haute Provence Observatory with his electron camera, coupled with a grating spectrograph, giving a dispersion of 170 Å/mm., were very successful. He managed to obtain sharp spectrograms of the Orion Nebula and of some faint galaxies with exposures of the order of a hundredth of the normal exposures used with ordinary telescopes.

In 1860 Donati, using a 16-inch lens in conjunction with a spectroscope constructed under the guidance of Amici, at the old Florence Observatory, nine years before it was transferred to Arcetri, observed and described the spectra of fifteen stars and their principal absorption lines. A few years later, Father Secchi with improved instruments tackled the problem of stellar spectroscopy in all its aspects. While Huggins in England was carrying out detailed studies of a small number of the brightest stars, Father Secchi planned to examine large numbers. In his words: 'I intended to discover whether as there are so many stars, their composition was proportionally varied. This was my problem, and having been very fortunate in improving my instruments of observation, I obtained better results than I hoped. . . . The instrument which we have temporarily set up

for these investigations, consists of a flint prism six inches in diameter having an angle of about 12°. This prism is placed in front of the objective glass of the large 9-inch refractor. Economic reasons have compelled us to limit ourselves to this size of prism, thereby losing more than half the aperture of the refractor available. The results obtained are indeed satisfactory. The light is much brighter than when we inserted a direct vision prism between the objective and the eye-piece, although the dispersion is four times as much. The prism was made by Mr. Merz of Munich, who states that he met with considerable difficulties in the process. We believe this since the prism is of a high precision.'

With this objective prism Father Secchi could soon discover 'that while the stars are in such a great number, their spectra can be reduced to a few and well defined forms which for brevity we call "types". The study of the stars has occupied me for many years: I examined almost all the principal stars and many others, at least 4,000 all together because apart from the principal star I also examined those around it.'

As has already been pointed out, photography quickly replaced the arduous and incomplete visual observations especially in the matter of locating and identifying the very numerous lines and bands in stellar spectra. In this field, also, Pickering at Harvard College Observatory completed a vast programme of observations, which formed the foundation of all subsequent work.

The easily perceptible colours of the brightest stars are themselves a sure indication that their surfaces are not all at the same temperature. Whereas yellow stars, such as Arcturus, Capella or Pollux, must have nearly the same temperature as that of the Sun, white or bluish stars like Sirius and Vega will be hotter, and orange or red stars like Betelgeuse and Antares will be cooler. Each of these types or classes, presents a characteristic and easily recognizable spectrum, and it was by means of their spectra that Father Secchi was able to establish three fundamental types among all the stars observed. The first comprises the white stars, the continuous spectrum of which is brightest in the violet region and is crossed by a few intense lines of hydrogen, the Balmer series. The second type, consisting of yellow stars, has a continuous spectrum which is brightest in its yellow region and is crossed by fainter but more numerous lines of hydrogen and metals. Finally the third type, which consists of red stars, has a spectrum which is most intense in the red region. This third group Secchi subdivided further. In the spectra that he called group 3 the

continuum is crossed by bands which have their head towards the violet while in group 4 the heads of the bands are towards the red.

The solar spectrum, which can be studied in much greater detail than the spectra of stars with their smaller dispersion, soon revealed some of the secrets of the constitution of the Sun, and the interpretation of its spectrum was assisted by our ever-increasing understanding of atomic physics. Rowland's great map of the solar spectrum with its accompanying catalogue of lines specified by their wavelengths expressed to 0·001 Å, allowed many of these to be identified with lines in the spectra of terrestrial elements. Later Rowland's map was completely revised and extended to include the infrared by observations made at Mt. Wilson. In this the number of identified lines was greatly increased, and the intensities of the lines were given on an empirical scale as Rowland had done, not only for the ordinary spectrum of the solar disc but also for the spectrum of sunspots. Furthermore, the lines were classified according to temperature and pressure, and in many cases the ionization potential was also given. With the Rowland Revision, as this work is known, we began to have information regarding the conditions under which spectral lines are produced and this, together with our understanding of spectral series of various elements, permitted the determination not only of the identity of those elements themselves, but also of their quantities and physical conditions.

The spectrum of the Sun is essentially one of lines superimposed on a continuous background. Among the most intense lines are those of ionized calcium (H and K) in the violet, and the lines of the Balmer series of hydrogen the intensities of which increase towards the red where the most intense of all is located, the Hα line or Fraunhofer's C line. The sodium lines in the yellow and those of magnesium in the green are also of exceptional intensity. All the other lines, of various intensities, are produced by the elements of the periodic table. The majority of these elements have already been identified in the solar spectrum. Those elements which have not yet been found, or may never be found, are not necessarily absent in the Sun. All that can be said is that they are not observable in the layer which produces the absorption lines either because they occur in too small quantities, or because they are confined to deeper levels.

All the solar radiation of wavelength shorter than λ 2900 Å is absorbed by a wide absorption band due to ozone in the stratosphere of the Earth, and hence observations made through the terrestrial atmosphere can tell us nothing about the ultraviolet spectrum of the

Sun beyond λ 2900 Å. Recently, however, small, automatic grating spectographs have been carried by rockets to altitudes exceeding 60 miles above the ozone layer. By this means the ultraviolet spectrum of the Sun from λ 2900 Å to the first line of the Lyman series of hydrogen at λ 1216 Å has been recorded. The ionized magnesium doublet in the neighbourhood of λ 2800 Å, consisting of two intense absorption lines with a bright central reversal, has thus been photographed, as well as numerous other absorption lines still to be identified. Moreover, these spectrograms taken at great heights above the Earth, show very clearly the Lyman α line in emission. Further interesting discoveries are to be expected from photographs taken outside the atmosphere of the Earth. At longer wavelengths than that of the Hα line there are characteristic bands due to molecular oxygen in our own atmosphere. Above λ 10,000 Å there are other wide and intense bands due to water vapour and carbon dioxide, also of terrestrial origin. Such bands can be immediately distinguished from those of solar origin, since their intensity varies with the altitude of the Sun above the horizon, according to the relatively long or short path of the rays of the Sun through our atmosphere. In addition to these terrestrial bands and the atomic lines of the Sun there are a number of bands in the solar spectrum which are due to molecules on the Sun, some of which have been identified with certainty as being those of cyanogen (CN) and of the hydrides CH, NH, and OH. Other hydrides which have been identified are those of magnesium and aluminium, as well as the oxides of magnesium, aluminium, titanium and zirconium.

The lines and bands of the upper layers of the Sun's atmosphere do not exhibit marked variations of intensity. It is only when we pass from the centre of the disc towards the limb that slight variations of intensity and structure are encountered. These are due to the different conditions of the gases, and hence to the various spectroscopic levels that are observable. In the sunspots the differences between their spectra and that of the photosphere are more obvious both in the intensity and the appearance or disappearance of lines and bands. From the study of the spectrum of the sunspots it is possible to deduce the difference between the physical conditions of the spots and of the photosphere. Substantially this consists of a lower temperature in the case of sunspots. There are numerous stars whose spectra are identical with that of the photosphere of the Sun, and others whose spectra are identical with that of sunspots.

The conclusion to be drawn from all this is that the absorption lines of the solar spectrum are for the most part due to atoms, which are in a given condition of excitation in the outer layers of the Sun. These layers are very thin. The temperature in them is lower than that in the inner parts of the layers on account of radiation towards the outside. As a result a selective absorption at various wavelengths is produced which depends on the various elements. It is for this reason that the layer responsible for this effect is known as the 'reversing layer'. Below this level the photosphere, which increases in density and temperature, is no longer transparent to the different radiations. This opacity produces a continuous spectrum like that produced by an incandescent solid body. This interpretation is confirmed by observations. When it is possible to observe the reversing layer isolated from the photosphere, it is found that at the moment when the continuous spectrum vanishes, all the absorption lines are reversed, becoming emission lines. This occurs during total solar eclipses, immediately before the second contact and again after the third. At these times, when the photosphere is completely covered by the Moon, the spectrum of the reversing layer consists of emission lines.

Each absorption line should have a corresponding emission line, but the process of reversal being complicated by the temperature, the density and the height at which a given element occurs in the atmosphere of the Sun, the relative intensities of the lines vary from one spectrum to another. At still higher levels the greater part of the weak emission lines disappear, leaving only the more intense. This is the spectrum of the highest atmospheric level of the Sun which is called the 'chromosphere'. The upper limit of the reversing layer and the lower limit of the chromosphere may be considered to be in the zone in which the majority of the spectral lines disappear up to a mean level of about 400 miles above the photosphere. Above this limit, in the upper chromosphere, there remain only those gases which are most abundant in the solar atmosphere. These gases reach a height which averages from 6,000 to 9,000 miles or even more in the 'prominences', which are nothing more than eruptions from the chromosphere.

In the spectrum of the chromosphere the lines of the Balmer series are conspicuous. The Hα line, which is the most intense, gives the chromosphere its brilliant red colour. The H and K lines of ionized calcium are characteristic of the highest levels. The yellow D_3 line of helium although it does not appear in absorption is also one of the brightest.

The intensity of the absorption lines of the photosphere is very similar to that of the lines produced by an electric arc, whilst the intensity of the emission lines of the reversing layer is similar to that of the spark spectrum. Now if we consider the spark spectrum, we find that it is similar to the spectrum of stars of a type less advanced than the Sun, apart from the fact that, of course, the spark spectrum consists of bright lines while that of the stars consists of dark lines. This is the result both of the very gradual drop of temperature and of the rapid falling of pressure as we reach higher levels of the solar atmosphere, which leads to an increasing degree of ionization of the gases.

When we refer to the surface of the Sun as being constituted by the photosphere, the reversing layer and chromosphere, it must not be thought that we are speaking of really separate and distinct layers. The modern theory of the formation of the spectral lines indicates that the name, reversing layer, does not imply what its name suggests, because the absorption lines are produced in layers which are to be found at the same level as those in which the continuous spectrum originates. No definite layer exists therefore, in which the monochromatic absorption is produced. The distinction between photosphere and chromosphere is more definite. The former may be identified with the luminous surface of the Sun, and is limited by the Sun's clearly defined limb; the latter extends beyond this limit to a height of the order of 6,000 miles and is not visible except with the help of a spectroscope, or during a total solar eclipse. The well defined appearance of the solar limb is explained by the rapid decrease of pressure throughout the outermost layers of the Sun.

The study of the solar spectrum has helped considerably the interpretation of stellar spectra in general. Since Father Secchi proposed his fundamental classification many others have been attempted, which are also based on a sequence with one parameter. The earlier of these classifications were influenced by the general appearance of the spectra, but later different criteria were adopted, in order to improve the accuracy of the classifications. Nevertheless, it cannot be said that the one most widely accepted today, the result of the extensive work done at Harvard College Observatory, is entirely satisfactory, since it is still necessary to solve the problem of establishing well defined criteria for a classification which is based on physical principles in accordance with the theory of stellar atmospheres. In the meantime, the classification nowadays generally used

is that which has been adopted for the 225,300 stars in the Henry Draper Catalogue, and which is therefore known as the *Draper Classification*. In place of the Roman numerals employed by Father Secchi for his stellar classes, the letters of the alphabet were introduced at Harvard, and as the work proceeded on the stellar spectra obtained by means of the objective prism each different class or type was given a letter. When the sequence was then established it was found that the letters did not follow each other in alphabetical order. Moreover gradually the classification was simplified by dropping some letters altogether. Finally, the classification of stellar spectra was established as follows (Plate 5):

```
                          → S
                          |
P    W–O–B–A–F–G–K–M
                  |
                  → R–N
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In this classification 90% of the stars in the Draper Catalogue belong to classes A, F, G, and K, the remaining 10% being distributed among the other classes. Since there is a gradual transition from one class to the next, decimal subdivisions were introduced and these are indicated by a number placed after the class letter. Thus a star belonging to class A5 has a spectrum intermediate between A0 and F0 with characteristics which are intermediate between those of the two classes and a G8 star is nearer to a K0 than to an F0 star. It is interesting to compare this new classification with Secchi's. Thus, his Class I (blue-white stars) is represented by classes from O to F in Draper's classification, his class II (yellow stars) by Draper's F to K5, and his classes III and IV (red stars) by Draper's M, S, N and R. Having established this general correspondence between the two classifications let us now discuss the characteristics of each of Draper's classes.

The first of the spectral classes is P. To this class belong those celestial objects which are called planetary nebulae. These are gaseous envelopes, highly rarefied and in a condition of high excitation. Such envelopes, which surround a central star of high temperature, are in some cases the product of a stellar explosion known as a nova. Since there is a connection or analogy between these spectra and those of stars of classes W and O it has been suggested that spectra of class P precede those of classes W and O in the sequence.

The choice of the letter W was due to the fact that the stars

assigned to this class were first studied by Wolf and Rayet, at the Paris Observatory. The spectrum of these stars is characterized by the numerous and broad emission bands originating from atoms with high ionization potentials and high ionization levels. In these spectra ionized helium HeII in emission is found. Two parallel branches may be distinguished within this class, one with lines of ionized carbon and oxygen and the other with lines of ionized nitrogen.

Class O contains a limited number of stars in which the absorption spectrum begins to make its appearance, with helium, carbon, oxygen, nitrogen and silicon, four or five times ionized, together with the line of ionized magnesium λ 4481 Å. The temperature of these stars continues to fall as class B is approached, with the progressive disappearance of the lines of ionized helium.

The violet region of the spectra of B-type stars is always extremely intense. They are characterized by narrow lines of oxygen, nitrogen and neutral helium. The neutral helium lines are most intense in classes B2 and B3, whilst the lines of the Balmer series of hydrogen increase in intensity throughout from classes B0 to B9. The enhanced lines of silicon, carbon, oxygen and magnesium are also present.

From A0 onwards, the helium lines are not to be found and in addition to the very intense lines of the Balmer series, we find those of singly ionized metals, such as calcium, magnesium and iron. These are replaced by the lines of the neutral atoms from class F onwards. The H and K lines of singly ionized calcium CaII are very conspicuous and constitute one of the most marked characteristics of these spectra. Their intensity reaches a maximum in class G0, which is that to which the Sun belongs. Throughout class F the lines of hydrogen continue to fade, whilst in class G the lines of neutral atoms increase in intensity. The spectrum thus becomes similar to that of the Sun. The band which extends from λ 4299 Å to λ 4315 Å due to the molecule CH is characteristic of the solar spectrum, in which, however, without adequate dispersion, it appears as a continuous absorption. At the beginning of class F it is still obviously discontinuous. In class G the hydrogen lines do not differ greatly from the others. 'Enhanced lines' produced in terrestrial spectra by means of an electric spark, begin to weaken, whilst the arc lines appear with increasing intensity. The H and K lines of ionized calcium and the band mentioned above, provide the most marked absorptions in the spectrum, while the hydrogen lines continue to weaken.

In class K the lines of the arc spectrum are still numerous, while those of the spark spectrum disappear. In general, as the intensity of the spectrum in the violet decreases so that in the red increases. The lines of ionized calcium are still very prominent, and so is the line due to neutral calcium λ 4227 Å. After class K5 the appearance of stellar spectra becomes very similar to that of Secchi's class III. Bands due to titanium oxide make their appearance, and these are also met with in sunspot spectra. This is proof of the low temperature of these stars, as compared with stars of the preceding classes.

In class M, the lines of the flame spectrum are very intense, and the bands, principally those of titanium oxide, become increasingly numerous. The bands are most intense towards the violet end of the spectrum, and gradually decrease in intensity towards the red. The lines of ionized and neutral calcium continue to be conspicuous. A sub-class is characterized by the presence of hydrogen emission lines. Stars of this type are variable, and generally belong to the Mira (ο Ceti) type. The presence of lines of the flame spectrum and of bands proves that the temperature of these stars is lower than that of the stars of the preceding classes. Such temperatures are easily attainable in our laboratories. Hence one may be certain that the sequence of classes as given here is also a sequence marked by decreasing temperature.

At this end of the sequence are to be found the red stars. In addition to stars of class M, which derive directly from stars of class K, there are other stellar spectra in which the bands are well defined towards the red end of the spectrum and rather weak towards the violet. These are the stars belonging to classes R and N, which should be considered as branching off from class G, and the most noticeable characteristics of which are the bands due to CN (cyanogen), CO (carbon monoxide) and CH, while the H and K lines are also rather intense. In class N the FeI lines, the D lines of sodium and the λ 4227 Å are conspicuous while the hydrogen lines are very weak. On account of the distribution of energy within the continuous spectrum, stars of this type are very deep red in colour. Other stars, the spectra of which contain the zirconium oxide band, are to be assigned to class S, which should be considered as a third branch of the sequence, deriving from class K.

To the left of class K, therefore, there is a single sequence, but to the right of it, where the temperature is low enough to allow the appearance of compounds, there are several branches. This is explained by the fact that if the temperature is too high for compounds

to exist, the relative quantities of each element present are not important, as it is immaterial if the quantity present of a given element is doubled or halved. On the other hand, at temperatures which are low enough to permit the formation of compounds, a difference in the relative quantities of the elements will produce marked changes in the spectrum of the star. If, for example, there is only a limited amount of oxygen in the atmosphere of the star, carbon, which has a great affinity for oxygen, will combine with the greater part of it, and the other elements will not be oxidized, hence the spectrum will be characterized by bands of the carbon compounds. If, on the other hand, oxygen is abundant in the atmosphere of a given star, then all the carbon present will be oxidized, as well as the titanium. Thus the bands of titanium oxide characterize the spectra of stars whose atmospheres are rich in oxygen. Class S stars, in the spectra of which the bands of zirconium oxide appear, have not yet been fully explained theoretically, but it is permissible to suppose that something of the same sort occurs here. That we see the bands of titanium or zirconium, rather than those of other elements, is due to the fact that these bands lie well within the limits of the visible spectrum and are easily identifiable.

We may therefore conclude that whereas stars of class M have an oxidizing atmosphere, stars of classes R and N have a reducing atmosphere. Furthermore, in the case of high temperature stars, the properties of their matter is simple, whereas in those of low temperature they become complex. Low temperature stars, in which compounds first make their appearance, may thus represent the probable beginning of individual evolution. With decreasing temperature, liquids and finally solids will be able to form.

As a result of this classification, the chemical elements and compounds so far identified in the celestial bodies fall into a regular and continuous sequence. Hence those elements which appear at the beginning of the sequence become modified and disappear to be eventually replaced by others, which make their appearance as we proceed along the sequence. The question which arises here is whether we are dealing with an essential difference in the atmosphere of the stars which belong to various spectral classes. This would justify the old names of 'helium stars', 'hydrogen stars' and so on. It is more likely, however, that we are dealing here with a slow transformation due to different conditions of pressure and temperature in the external atmosphere of stars, which, although belonging to different classes, nevertheless contain the same elements.

In the first case, a regular variation from one class to the next would not be possible, and this is proved also by a class of double stars known as 'eclipsing variables'. The two components of these systems revolve around their common centre of gravity in a plane which is at right angles, or nearly so, to a plane tangent to the celestial sphere. Such stars are physically near to each other, often being separated by a distance only a little more than their diameter. Now, in such systems one of the components may belong, for example, to class A while the other belongs to class K. In such cases it is difficult to believe that all the metals were confined to one half of the star which divided to form the binary system, and that all the gases were confined to the other half. It is more likely that there exist some physical factors, which prevent the spectral lines of lighter gases from appearing in the spectrum of the K-type star, and the lines of metals from appearing in the spectrum of the A-type star.

This problem was clarified when it was shown that the sequences of Father Secchi and Draper are essentially dependent upon a decreasing temperature scale, whence it was possible to establish the physical connexion between the various temperatures and the criteria of classification, such as the presence and intensity of the various spectral lines and bands. After the first comparisons had been made between stellar and laboratory spectra, Lockyer almost reached the solution of the problem when he demonstrated the behaviour of the lines of the flame spectrum and of the 'enhanced' lines. The final solution was given by Megh Nad Saha. As a consequence of the rapid progress of atomic physics, he was able in his theory of thermal ionization to give a clear account of the observed phenomena.

We shall have more to say about this theory when we come to discuss stellar temperature. Here, to conclude our survey of stellar spectroscopy and of spectral classification, it will suffice to say that the ionization of an atom is determined by various conditions of temperature and pressure. A high temperature and a low pressure favour an increased ionization. The percentage of ionized atoms increases as the temperature rises and as the pressure drops, and hence there will be an intensification of the lines of ionized atoms (spark spectra) while those of neutral atoms (arc and flame lines) will be weakened. Calculation has shown that variations of temperature are more important than those of pressure in their influence upon the state of ionization. In the Draper classification the stars

are essentially arranged in order of decreasing temperature, and therefore of decreasing state of ionization. This explains the higher ionizations encountered in the earlier spectral types.

Investigations and observations carried out in the past have proved the practical value of the empirical system used in this classification. Recent investigations, however, attempt to reach a classification based mainly upon the special physical characteristics of the various types of stars. The new classification should be able to describe the stellar spectra numerically in terms of defined parameters. This is possible because spectra with higher dispersion are being studied. In fact the relations which exist between the width of the absorption and emission lines are becoming clearer, as well as the dependence of the lines upon the physical characteristics of the star, namely its absolute magnitude, its mass, its density and the energy distribution in the continuum, the latter being a very important factor of which the Draper classification takes no account.

In order to obtain a numerical expression of the behaviour of the spectral lines, it is not sufficient to consider only the temperature, but the abundance of atoms, both neutral and ionized, have to be taken into account. These and other parameters differ considerably for the various elements of which the stars are composed and furthermore our knowledge of the mechanism of radiation is not sufficient to enable us to reach a final physical classification of stellar spectra based on what we can observe of the outer atmospheric layers of the stars.

Up till now several criteria have been used to arrive at two-dimensional and three-dimensional spectral classifications. Morgan in his atlas of stellar spectra, sets out a series of qualitative criteria suitable for a two-dimensional system of classification (spectral type and luminosity) for stars belonging to classes from O to M of Draper's classification. The lines used for determining the spectral type and the absolute magnitude, are not the same for different spectra. Morgan has suggested a division in classes from I to V of decreasing luminosity, from supergiants to dwarfs, and from class B0 to M5.

In this new classification in class I we find the supergiants, in class II the bright giants, and in class III the normal giants, while class IV refers to subgiants and class V to dwarfs. The practice has grown nowadays of using the letters of Draper's classification followed by the Roman numeral of Morgan's classification.

In Draper's classification a well defined criterion of luminosity is

given by the lines of the Balmer series, the intensity of which grows rapidly with diminishing luminosity. The intensity depends not only upon the temperature but also on the luminosity and hence upon the electron density of each stellar atmosphere. Moreover the number of lines of the Balmer series which can be observed towards the ultra-violet depends upon the temperature and luminosity, but mainly upon the latter, since an increase in the electron density produces an increase also of the electric field. As a consequence of this the last lines of the Balmer series become confused because of the Stark effect. Therefore the intensity of a line of the series and the number of lines which can be observed, enable us to obtain both the temperature and the electron density which are the essential characteristics of the spectral type.

The classification suggested by Chalonge and his associates at the Astrophysical Institute in Paris is based on a similar line of thought. This group of workers make use of: (1) the 'Balmer's discontinuity' (D) which is a function of the spectral type and of the luminosity and which has a behaviour similar to that of the lines of the Balmer series; (2) the wavelength λ at which the discontinuity occurs and which is closely related to the number n of lines that can be observed. The limit of the Balmer series occurs at λ 3646 Å at which point there occurs a marked and sudden decrease of intensity in the continuum of the spectra of the stars, which is known as 'Balmer's discontinuity' (D). This is due to the ionization of the hydrogen atoms, beginning with the second excitation level, and its measurement provides some information about the electron pressure and the temperature of the absorbing medium.

Chalonge and his associates have drawn diagrams in which the values of λ and D of the stars studied are given. They have in this way obtained in the diagrams areas containing stars of the same temperature and of the same luminosity. Later this classification was extended by Chalonge to a three-dimensional one by taking into account the absolute spectro-photometric gradient of the continuum in the spectral region between λ 3800 and λ 4800 Å. The above classification stops at class G0 since it is not possible to determine either the value of the discontinuity, or the number of lines in spectra beyond class G0, because of the multitude of lines and bands of absorption covering the continuum as well as the last lines of the Balmer series.

From the detailed study of their spectra, the chemical composition of red stars and also, to a certain extent, of blue stars appears to be

abnormal. This would strengthen the suggestion that what is required is a multi-dimensional classification, which would take into account not only temperature and pressure but also one or more parameters which depend upon the chemical composition of the various stars.

CHAPTER IV

Spectrophotometry of the Stars

Rapid progress in the technique of celestial spectrophotometry has resulted from the necessity of determining accurately by differential or absolute means, the intensities both of the continuous spectrum and of the lines or bands of stellar spectra. The spectral lines, whether emission or absorption, have varying intensities and widths. Rowland, in his fundamental work on the solar spectrum, gave to the spectral lines empirical numbers which represented, on an arbitrary scale, their combined widths and intensities. Once these characteristics had been recognized as being a function of the number of atoms involved in the formation of the various lines, it was possible, on the basis of theoretical considerations, to establish a calibration of Rowland's scale in terms of N, the number of active atoms. An examination of many multiplets in the solar spectrum led to the discovery of a relation between log N and Rowland's estimated intensity, which has been found to depend upon wavelength. By means of successive approximations the following formula was obtained:

$$\log N = B \log A$$

where A is a function of Rowland's intensity and B is a function of λ. From this calibration can be derived the relative numbers of active atoms in the outer atmosphere of the Sun which produce the spectral lines in the various regions of the solar spectrum. On the assumption that the stars are in thermodynamic equilibrium, and that the atoms at different levels are equally effective in the production of a given line, Adams and Russell have extended the investigation to stellar atmospheres in general. They obtained an equation which connects the relative number of atoms producing the same line in the spectra of different stars, with the relative number of the normal neutral

atoms, their excitation potential, their state of ionization, the electron pressure and the temperature of the star.

In the meantime, ever more sensitive microphotometers were being designed, by means of which Rowland's empirical estimates and those of his successors were being replaced by exact measurements of the quantity of energy absorbed or emitted by the lines and of that of the continuous spectrum. Since these measurements are nowadays made only on photographs, the microphotometer assumes a very important role. In the case of spectra it is more than ever necessary to employ recording instruments in order to have a continuous diagram of the intensity variations in their different parts (fig. 3). The deviations of the galvanometer caused by the variations of current produced in the thermocouple or photoelectric cell, by the different degrees of darkening of the spectrogram, are registered as a continuous trace on photographic paper. Thus a diagram is obtained of the degree of darkening through the whole extent of the continuum and the emission or absorption lines that are present in the spectrum. Various types of these instruments have been con-

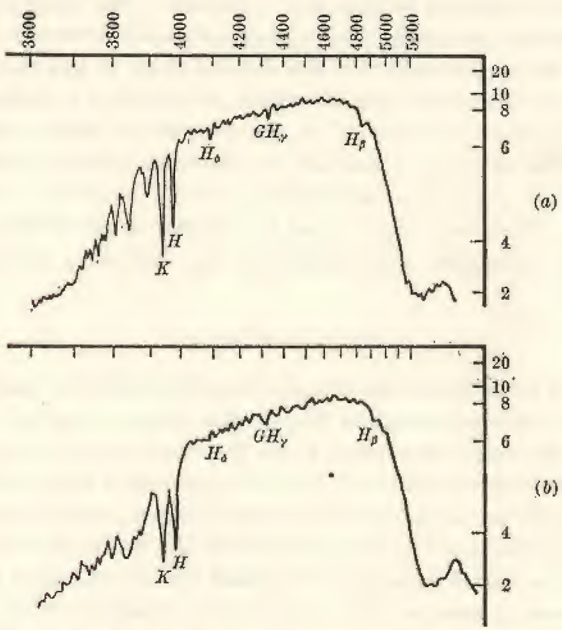


FIG. 3. Microphotograms of the spectrum of η Aquilae.
(a) at maximum (b) at minimum

structed, though their principle is always the same, and their sensitivity and accuracy is such that the details of every point in the spectrum can be recorded, and even considerably magnified. From the curves obtained with the microphotometer it is possible to deduce the intensity of the continuous spectrum and of the lines. Their form can be determined by means of a calibration curve which shows the relationship between the various degrees of darkening of the emulsion and the various intensities. This procedure in general is long and arduous especially when dealing with regions of the spectrum containing many lines. Recently a new form of the instrument has been developed, which gives the intensities directly. This is made possible by the use of a second photoelectric cell and a second galvanometer, added to those of the recording microphotometer.

Between the first galvanometer and the cell is interposed a diaphragm which has a form corresponding to the calibration curve of that particular plate on which the spectrum under examination has been recorded. With this device the light reflected by the mirror of the first galvanometer is deviated by an angle which is proportional to the degree of darkening of the plate. The light passes then through the diaphragm and only a part of it is transmitted, a part which is proportional to the intensity. The combination of the second photoelectric cell and second galvanometer ensures that the light which is reflected by the mirror of the galvanometer registers the curves of intensity on photographic paper.

Minnaert and his colleagues, using this technique, have published a photometric atlas of the solar spectrum which reproduces in a large number of plates the curves obtained by means of the galvanometer, covering the whole solar spectrum from λ 3332 Å to λ 8771 Å. The ordinates of these curves, which vary from 0 for the transparent plate, to 100 for the continuous spectrum, thus give the intensity of the spectrum and that of every point of the various lines. This atlas, together with Rowland's photographic map, or the Mt. Wilson map, provides us with a complete documentation on the subject of the solar atmosphere. It is also an excellent basis for our knowledge of stellar atmospheres, the spectra of which cannot be obtained in such detail.

Thus in place of the empirical estimates we are now able to substitute precise measurements of what is known as 'equivalent width' of the spectral lines. In the empirical estimates the intensity was simply a combination of the darkening at the centre of the line and the width of the line, both of which are extremely variable in different

elements for various reasons. The microphotometer shows the line profile, that is to say its shape from the point at which it emerges from the continuous spectrum, to the point at which it returns. By equivalent width is meant the width of a completely black line which absorbs from the continuum an amount of energy equal to that absorbed by the line which is being studied. By taking into account the resolving power, the instrumental profile, which depends upon the spectrograph used, the true profile and equivalent width of many lines in the solar and stellar spectra have been determined. Since a well marked relationship has been found to exist between the logarithm of the number of atoms producing a line, and the logarithm of its equivalent width, it is possible to deduce the number of atoms and thus to arrive at a knowledge of the composition of stellar atmospheres. This relationship depends on the causes which produce the lines, namely the resonance width, Doppler shifts due to thermal motions and turbulence. Where a relatively small number of atoms is active, the broadening due to the Doppler effect predominates, and the 'curve of growth', which represents the relationship between the logarithm of the number of atoms and that of the equivalent width, rises rapidly. There follows a transitional stage in which the equivalent width remains unchanged, although the number of atoms increases, and finally when the number of atoms is very great, the broadening due to resonance predominates and the equivalent width once again begins to increase rapidly.

From spectrophotometric investigations of this type, it has been possible to obtain a quantitative analysis of solar and stellar atmospheres, the only limitation being the depth of the atmosphere which can be penetrated by the spectroscope. In the case of the Sun, since instruments having much greater dispersion can be used, the analysis is very detailed. Even in the case of the stars of various types, remarkable results have already been obtained.

The main fact revealed is that for all stars, the Sun included, hydrogen is by far the most abundant element. The difference which is found in the abundance of the other elements is probably due to the original formation and successive evolution of the Sun. Possibly the various elements were produced in some way as yet unknown, out of a primeval simple element like hydrogen. The most abundant elements then would be those which for some reason were produced in great quantities, while those which are scarcer, either had less chance of being formed, or were transmuted into other elements with much greater ease.

The uniformity of composition of the universe is evident from this quantitative analysis. Russell had already called attention to the similarity in composition of the Sun, meteorites and the Earth itself. Although the light elements, particularly hydrogen and helium, are much more abundant on the Sun and the stars than on the Earth, metals, such as iron, titanium and nickel, have almost the same percentage distribution in all these bodies. Perhaps this is related to the formation of the elements at the time of the origin of the universe and of the solar system.

It is customary to compare the abundance of various elements with that of hydrogen, and to take 12 for the logarithm of the abundance of hydrogen atoms. This is done in order to avoid negative logarithms for the abundance of other atoms.

When we take $\log N_H = 12$, we find that for the Earth's crust $\log N_{\oplus} = 6{\cdot}2$. For both the Sun and the stars we find that the logarithm of the abundance of atoms of He is 11·3, of lithium 0·8, and of berillium 2·4. It is known that nuclear reactions in the interior of the stars are responsible for the conversion of hydrogen into helium, and the very low values of abundance for lithium and beryllium can be explained if we assume that these elements are exhausted before the above-mentioned nuclear reactions take place. For carbon, $\log N_C = 8{\cdot}3$, its abundance does not change, since as we know this element acts as a catalyst.

It is clear therefore that the ratio of abundance helium and hydrogen He/H has a particular significance in the study of stellar evolution and may indeed allow us to estimate the age of the stars. Nitrogen and oxygen have a $\log N = 9$, approximately. Sodium, magnesium, silicon and other metals, have a smaller $\log N$, between 8 and 6, and for iron $\log N_{Fe} = 6{\cdot}9$. It is noticeable that as the atomic number increases, the values of $\log N$ become smaller, and also that elements having an odd atomic number are rarer than those having an even atomic number.

Although generally speaking it can be stated that the majority of stars have a chemical composition which is nearly uniform, the more detailed examination which nowadays is carried out, of stars of various types, indicates considerable differences and abnormalities in the chemical composition of the stars.

We shall see later on, that stars are divided into 'giants' and 'dwarfs' and also into two 'populations' having well distinct characteristics which determine their dynamical and spatial characteristics as well as their age. Stars of 'population II' which are older than

stars of 'population I' have one thing in common. The ratio of carbon, nitrogen and oxygen to hydrogen, as well as that of the metals to hydrogen, are $\frac{1}{15}$ and $\frac{1}{3}$ respectively of the ratio for stars of 'population I' such as the Sun. Stars with spectra containing metallic lines, and dwarfs which have a radius a little smaller than that of the Sun (sub-dwarfs) show an abnormal Balmer discontinuity. It is found that in the former, carbon is absent, while the sub-dwarfs have twice as much carbon as normal stars. Several hypotheses can be formulated from this evidence, but perhaps it is premature to assume that this type of star has a special chemical composition.

Another important problem which at present is being studied by spectrophotometric means is that of the presence of isotopes in stellar atmospheres, in connection with stellar evolution. It is extremely difficult to determine the abundance of deuterium in the Sun because of its scarcity. The line Dα of deuterium is extremely near to the Hα, and during violent eruptions on the Sun, it is possible that deuterium is formed continuously.

Another problem which is of extreme interest is that of establishing the ratio of C^{12} to C^{13} in various stars. Results so far obtained indicate that there are differences in this ratio for the various types of stars, and possibly the same applies to the ratio of He^3 to He^4. It is well known that these elements are those which play an important part in the cycles of production of stellar energy. We should remember that with the present spectrophotometric methods, it is possible to probe and study only the spectra of the outermost layers of the stars and of the Sun. These layers are relatively thin, since if they were thicker the opacity of the gas would prevent the study of the lower and deeper layers. This opacity, as it can be found in laboratory experiments, is probably due to the ionization of the gases. Because of the ionization, the free electrons dissipate their energy in heating the gases, thereby making the solar atmosphere become less transparent and reach opacity when the pressure is only one thousandth of an atmosphere. The transition from opacity to transparency is proportional to the square of pressure, as gradually we pass from the internal layers to the outer ones. So from the photosphere, where the spectral lines in absorption are formed, we pass to the chromosphere where the lines are observed in emission. In a fairly thin layer of gas, therefore, several thousand lines are produced. This can also be proved in a laboratory when observing a layer of sodium vapour having a thickness of a fraction of an inch and a pressure less than one atmosphere. The sodium vapour when it is excited by

a flame or by the arc produces the D lines in double reversal, much wider and intenser than the corresponding lines which are observed in the spectrum of the Sun.

When the degree of ionization is less, for example as a result of a reduction in temperature, then it will be possible to see a little deeper into the atmosphere of the star. We have an example of this in the case of sunspots where the temperature is about a thousand degrees lower than in the photosphere.

The intense spectral lines, which are produced by a large number of atoms, indicate that we are dealing here with a deeper layer of the stellar atmosphere. If from the wings of the lines we move to the centre of them, we can then examine layers of ever-increasing height. The narrow and weaker lines of the spectrum, on the other hand, represent the lower layers.

If we consider the Sun which presents a disc of large dimensions, we can, by means of a special instrument known as the 'spectroheliograph', study the distribution of the gases which rise to its surface. In fact by isolating the centre of the absorption lines of hydrogen and calcium (Hα; H; K) we obtain the distribution of these gases at their highest levels.

CHAPTER V

Physical Characteristics of the Stars

The sequence of stellar spectra is essentially related to decreasing temperature. Therefore it is important to be able to determine the temperature of different types of stars and this can be done by following the methods used by physicists for measuring the temperature of radiating bodies.

If the stars could be treated as 'black bodies', namely as perfect radiators, the problem would be simplified, but we know that in fact they are not, since they do not have a continuous spectrum. Nevertheless all the stars which have a continuous spectrum crossed by lines can be considered almost as black bodies. In the case of nebulae, and of stars having spectra which contain emission lines, we have to turn to other methods in order to determine the temperature. On the whole there are several ways by which we can determine the temperature of the stars, which is such an important physical characteristic. When we talk about temperature of a star, we are referring to its surface temperature; to determine that of its internal layers we must rely on theoretical considerations.

By means of Planck's equation, which gives the quantity of energy radiated by a black body at every wavelength, and by means of Stefan and Wien's laws which are derived from it, we can calculate the temperature of a star.

Stefan and Wien's laws can be used when the quantity of energy radiated by the star at various wavelengths has been determined. There are also two other cases when these laws can be used and that is when we know either the total energy radiated at all wavelengths or the wavelength corresponding to the maximum intensity of the emitted radiation.

The energy distribution throughout the visible and invisible regions of the spectrum of a star is represented by a curve which

can be directly compared with similar curves for a black body which has been raised to ever increasing temperatures. These curves demonstrate that, in accordance with Wien's law, the wavelength of maximum intensity varies inversely to the temperature. The area enclosed by each curve, that is the total radiation, is proportional to the fourth power of the temperature, as stated by Stefan's law.

The first step is to determine, with a spectrobolometer, the distribution of energy throughout the spectrum of the Sun from the limit in the ultraviolet imposed by our atmosphere (λ 2900 Å) to the infrared (λ 20,000 Å). The maximum of the curve occurs in the visible region at λ 4700 Å. If similar curves are plotted for two perfect radiators at, respectively, 5,750° K and 6,150° K, it is found that the curve relating to the Sun falls, with minor deviations, between these two. At a wavelength of λ 5000 Å the Sun radiates slightly more energy than a black body at a temperature of 6,150° K, and hence the regions emitting these radiations must be at a higher temperature. In the extreme red, the Sun's radiation corresponds to that of a black body at a lower temperature, but in the ultraviolet, where there are so many spectral lines, the Sun's temperature drops rapidly. From this it must be concluded that the Sun does not behave like a perfect radiator, but that its temperature varies between 5,800° K and 6,300° K according to the depth of the layer that can be observed. Therefore 6,000° K may be taken as the approximate temperature of the photosphere, with a variation of 5% on either side of this value.

In the case of the stars we are faced with the problem of determining the temperature of the different classes. Various methods, in addition to that already described for the Sun, are available. Using a very sensitive radiometer in conjunction with a spectroscope mounted at the focus of the 100-inch telescope at Mt. Wilson, Abbot succeeded in measuring the energy emitted by some of the most luminous stars in the northern hemisphere. The Planck curves which best fitted his measurements indicated that the temperatures of stars of various classes were as follows:

stars of class A0 such as α Lyrae	14,000° K
stars of class F5 such as α Canis Minoris	8,000° K
stars of class G0 such as α Aurigae	5,800° K
stars of class K5 such as α Tauri	3,000° K
stars of class M0 such as α Orionis	2,600° K

Assuming the stars to be perfect radiators, Planck's formula can be

used to calculate the density of their luminous flux, that is the quantity of radiation emitted per unit area per second between wavelengths λ and $\lambda+d\lambda$. From this their actual total luminosities may be derived if their radii are known. When we convert luminosity into absolute magnitude, a simple relation can be derived which links the absolute magnitude, temperature and radius of a star. From this relationship any one of these quantities can be calculated if the other two are known. The absolute magnitude may be either visual or photographic according to whether we refer to an effective wavelength of λ 5290 Å or λ 4250 Å respectively, and the formulae have different numerical factors depending on which of the two magnitudes is used. We have already seen that the difference between the photographic absolute magnitude (M_p) and the visual (M_v) is the colour index i of the star. We then have:

$$i = M_p - M_v = \frac{7200}{T} - 0{\cdot}64$$

where T is the absolute temperature and hence the colour index is, as Father Secchi suspected, a function of temperature only. At low temperatures the colour index is positive, and may attain a very high value. At high temperatures it becomes negative, and may approach a limiting value of $-0{\cdot}64$. While there is no limit to the value of the colour index in the case of red stars, there is such a limit for blue stars, as has in fact been verified experimentally.

The many determinations of the colour indices of stars of various types yield the following temperatures:

B0	23,000° K
A0	11,000° K
F0	7,500° K

From class G0 onwards it is found that, for the same spectroscopic characteristics as those of the Sun, there are two slightly different values for the colour index, so that after this class the sequence has to be divided into two branches. We shall see later that these consist of stars which are either much larger than the Sun or smaller, and from this has been developed the distinction between giants and dwarfs. Giants of class G0 have a positive colour index 0·67 while dwarfs of the same class have a colour index 0·57 and the temperatures obtained are 5,000° K and 6,000° K respectively. In classes K0 and M0 the differences are still more marked:

K0: giants $i=1{\cdot}12$ $T=4{,}100°$ K: dwarfs $i=0{\cdot}78$ $T=5{,}100°$ K
M0: giants $i=1{\cdot}73$ $T=3{,}100°$ K: dwarfs $i=1{\cdot}45$ $T=3{,}400°$ K

When we know not only the colour index of a star but also its spectrum, we can measure the latter spectrophotometrically at various wavelengths and determine the temperature in the same way as has been described in the case of the Sun. It has been found that at the end of the sequence, the stellar temperatures are of the same order as those which can be obtained in the laboratory with an electric arc or furnace. The temperature may also be derived from the bolometric correction (p. 37) by means of a formula analogous to that given above. Here, however, the problem is complicated by the absorption effect of the terrestrial atmosphere in the ultraviolet and in the infrared and the simple formula is only applicable to yellow and red stars. Pettit and Nicholson, working with the 100-inch reflector of Mt. Wilson, obtained values for these stars which are in good agreement with those obtained by other methods; namely:

G0	5,500° K	M0	3,100° K
K0	4,200° K	N	2,700° K

In the case of variable stars of class M it is found that their temperature at maximum brightness is 2,300° K, and at minimum, 1,650° K.

Another method, unlike those which are based on the spectral energy distribution or on the total radiation of a star, is based on the appearance or disappearance of the spectral lines, and therefore of the intensity with which these appear in stellar spectra. This method has been greatly developed since Megh Nad Saha put forward a theoretical explanation of these phenomena in 1920.

Starting with the fundamental idea that the dissociation of an atom into a positively charged ion and one or more negatively charged electrons is a phenomenon of the same nature as the reversible dissociation of a gas, we can assume that in the ionization of a gas such as calcium we have:

$$\mathrm{CaI} \rightleftarrows \mathrm{CaII} + e - U$$

where CaI and CaII represent the neutral and the singly ionized calcium atom, e represents a free electron, and U the energy required to effect the ionization. Saha by following the general laws of physical chemistry, arrived at the following formula, which has been extensively applied in astrophysics and has explained many characteristics

of stellar spectra. Let x represent the degree of dissociation, that is the proportion of ionized atoms of a given element, T the absolute temperature, I the ionization potential of the element expressed in volts, P the total pressure of the gas, then we have:

$$\log \frac{x^2}{1-x^2} = -\frac{5036\, I}{T} + 2{\cdot}5 \log T - 6{\cdot}5 - \log P$$

By means of this formula it is possible to calculate theoretically the degree of ionization of an element, once the other quantities in the equation are known. Conversely, if x and I can be determined, we shall know something of the behaviour of temperature and pressure. This can be made use of to determine either the temperature or the pressure when only one of these is known. Now the degree of ionization can be deduced from the presence and the intensity of a chosen set of lines in a given spectrum or their absence. The equation shows that, under given conditions, the degree of ionization is low for high values of I. The higher the ionization potential, the higher must be the temperature in order to maintain a given degree of ionization. The most notable example of this is helium, which has the highest known ionization potential (24 volts), and which is found in great abundance in the spectra of the hottest stars. On the other hand, the lower the pressure, the more complete will be the ionization. When 100% of the atoms are ionized then $x=1$.

As the pressure diminishes, the number of collisions between electrons and ions will decrease, so that their recombination will become less frequent even though the velocity with which they are produced remains the same. In other words, the ionization of a gas occupying a given volume will increase the pressure, owing to the electrons which are liberated, and hence if the pressure is increased, this will tend to be neutralized by a reduction of the ionization. It has in fact been found experimentally that many lines of spark spectra can easily be produced by an electric arc operating in a vacuum.

By means of Saha's formula it is possible to calculate the percentage of ionized atoms for the temperature existing in a medium where there is a pressure gradient, similar to that existing in the outer layers of the Sun. Thus, although the pressure of the reversing layer and of the chromosphere are not accurately known, it is nevertheless certain that at the temperature of these layers (6,000° K to 7,000° K) the atoms of calcium, both neutral and ionized, will be found in great numbers. This accounts for the presence of the lines

of both the neutral and the ionized atoms of this element. At great heights above the reversing layer the pressure is extremely low, while the temperature, assuming that radiative equilibrium is maintained, has not greatly decreased. Under such conditions the degree of ionization will be increased until it is complete and the enhanced lines will be predominant. This has in fact actually been observed. In a similar way, many observed facts, involving other elements than calcium, in the solar spectrum can be explained. Hydrogen, on account of its high ionization potential, can never be completely ionized on the Sun. Helium will be even less ionized, and its enhanced lines will be found only in the spectrum of the highest layers of the Sun.

When Saha's formula is extended to the second degree of ionization, and the intensities of lines produced by different conditions of excitation are studied, it can be shown that the hottest stars, those of class O, in which the atoms of calcium are doubly ionized, have a temperature of 20,000° K, and that B8 stars, in which all the calcium atoms are singly ionized, have a temperature of 13,000° K.

When all these results are combined, the mean effective temperature of the photosphere of stars of the various spectral types can be deduced. The term photosphere here refers to those regions of a star from which the greater part of the radiation escapes directly into space without being absorbed or dispersed on the way. From the lowest levels of the photosphere, which are the hottest, only a small part of the radiation emitted is lost into space, while from the higher levels of the photosphere almost all is lost in space. It is calculated that the temperature immediately above the photosphere is 85% that of the effective temperature. Then it decreases slowly towards the exterior, while both density and pressure approach zero.

The mean temperature of the stars may be fixed as follows for the various classes:

		GIANTS	DWARFS
B0	23,000° K		
A0	11,000		
F0	7,400		
G0		5,600° K	6,000° K
K0		4,200	5,100
M		3,100	3,400
N		2,600	

The mass of a star is another physical characteristic which is of the greatest importance to an understanding of its constitution. The

mass of the Sun is easily determined by its gravitational effect on the planets. Its measure is given by the acceleration that it produces in their motion. Thus from the size of the orbit of the Earth and the period of revolution around the Sun, it can be calculated that the solar mass is about 330,000 times greater than that of the Earth.

The discovery of binary stars was the point of departure for the proof of the universal validity of the laws of Kepler and Newton. Binary stars are systems consisting of two stars, which may be of the same or of different size, which revolve around their common centre of gravity in accordance with the laws of universal gravitation. It follows from Kepler's third law that, if the semi-major axis of the relative orbit of a binary system can be determined and called a'' (measured in seconds of arc), and its distance from the Sun expressed as the parallax p in seconds of arc, then the total mass of the system ($\mathfrak{M}$), consisting of the sum of the masses of its two components ($\mathfrak{M}_1+\mathfrak{M}_2$), is given by:

$$\mathfrak{M} = \mathfrak{M}_1+\mathfrak{M}_2 = \frac{a^3}{t^2\ p^3}$$

where t, the period is expressed in sidereal years, a in units of the semi-major axis of the Earth's orbit, that is the astronomical unit (A.U.), and $\mathfrak{M}$ in terms of the mass of the Sun. The individual masses $\mathfrak{M}_1$ and $\mathfrak{M}_2$ can only be derived in those special cases when, for example, it is possible to establish the positions of one or both components relative to other stars which are apparently near to the binary system in the sky. In this way their orbital motion may be distinguished from the proper motion of the centre of gravity of the system, and the relation:

$$\frac{\mathfrak{M}_2}{\mathfrak{M}_1+\mathfrak{M}_2}$$

can at once be determined. There are not many binary stars whose total or individual mass can be calculated. There are hundreds of systems, however, for which when the parallax is known the mass of the system can be calculated. This in spite of the fact that their orbit cannot be defined with sufficient accuracy because they have covered too small a part of it since they were first observed. Such determinations have shown that the mass of the components of visual binaries are in general of the same order as that of the Sun, so that the mass of the system is equal to 2. The total mass of Capella (α Aurigae) is 7·5 that of the Sun (usually expressed as

7·5 ⊙ where ⊙ is the symbol for the Sun) while the individual masses of its two components, which have absolute magnitudes −0·2 and 0·1, are respectively 4·2 ⊙ and 3·2 ⊙. A system of such a mass is already exceptional. At the other end of the scale, we have the system known as Krüger 60, the components of which have absolute magnitudes of 11·8 and 13·4, the total mass is 0·45 ⊙, and the individual masses of its components are respectively 0·27 ⊙ and 0·18 ⊙. Thus these two systems, which have a difference of 12 magnitudes corresponding to a ratio of 60,000 to 1 as far as their luminosity is concerned, have a mass ratio of 25 to 1. It may be concluded that for these stars the range of mass is in general not very great.

The fact that the components of visual binaries can be individually seen means that they are relatively close neighbours of the solar system and hence have large parallaxes. The majority of them belong to the later spectral classes. In order to obtain statistical data regarding the masses of more distant stars, or of stars of other spectral classes, we must have recourse to spectroscopic binaries and eclipsing binaries.

The former, as their name indicates and as we shall explain in more detail later, are binary systems with components which are too close to one another to be separated visually but which reveal their binary nature spectroscopically by means of the Doppler effect. In general for this type of system, unless other data are available, it is not possible to discover the inclination of their orbit to the plane at right angles to the line of sight. When other elements of the orbit are known it is possible to determine $\mathfrak{M}_1 \sin^3 i$ and $\mathfrak{M}_2 \sin^3 i$ if the spectra of both components are visible. More generally, however, only one is visible and in this case the 'mass function' can be determined:

$$\mathrm{f} = \frac{\mathfrak{M}_2{}^3 \sin^3 i}{(\mathfrak{M}_1+\mathfrak{M}_2)^2}$$

When both components are visible it is possible to set a lower limit by making $\sin^3 i=1$, ($i=90°$). In this way it has been established that many of these components have masses comparable with that of the Sun, though some are much greater. For example, two high-temperature stars have components whose lower limits of mass are as follows:

Henry Draper Catalogue No. 698; mag. 7·1: Class B9
$\mathfrak{M}_1 \sin^3 i=113$, $\mathfrak{M}_2 \sin^3 i=45$, $\mathfrak{M}_2/\mathfrak{M}_1=0{\cdot}4$
Henry Draper Catalogue No. 47129; mag. 6·1: Class O8
$\mathfrak{M}_1 \sin^3 i=76$, $\mathfrak{M}_2 \sin^3 i=63$, $\mathfrak{M}_2/\mathfrak{M}_1=0{\cdot}8$

therefore it is certain that among these systems there are some stars with a mass equal to 100 times that of the Sun. The following mean values may be accepted for the majority of spectroscopic binaries:

CLASS	$\mathfrak{M}_1 \sin^3 i$	$\mathfrak{M}_2 \sin^3 i$	$\mathfrak{M}_2/\mathfrak{M}_1$
B0	12	9	0·8
A0	2·3	2	0·9
F5	1·3	1·1	0·9

If the values of the mass of the stars obtained in this way are increased by 50%, we have values which are sufficiently accurate for statistical purposes. As we shall see later the relation between the masses depends on the luminosity of the two components, the ratio 0·9 corresponding to a magnitude difference of about 0·5.

In the case of those systems known as eclipsing binaries, the spectroscopic orbits of which are known, the masses of the components may be calculated without any statistical uncertainty since the inclination of their orbits is known. Since we, on Earth, observe the periodic eclipses of the two components, the inclination of their orbit to the line of sight must be close to 0°. It is among stars of this type that we find confirmation of the fact that the hotter stars are also much more massive than the Sun. On the other hand dwarfs which belong to the same class as the Sun have a mass which is equal to that of the Sun. The primary component of the ζ Aurigae system is a K4 star with an absolute magnitude of $-5{\cdot}1$, and is therefore to be considered as a giant. Its mass is about 17 times that of the Sun. The data that have been derived from these systems may be summarized as follows:

CLASS	ABSOLUTE MAGNITUDE	$\mathfrak{M}_1$
O8	−7·8	45
B0	−4·5	18
A0	+0·7	2·3
G1 (dwarfs)	+4·5	1·1
M1	+7·7	0·6

All the data that have now been provided by binary systems of various kinds have made possible the confirmation of an important relationship between the mass and the luminosity of the stars, known as the mass-luminosity relationship, which was deduced theoretically by Eddington in 1924 from his investigations of radiative equilibrium. This relationship can be made clear by means of a diagram (fig. 4) in which the abscissae represent mean absolute magnitudes, and the

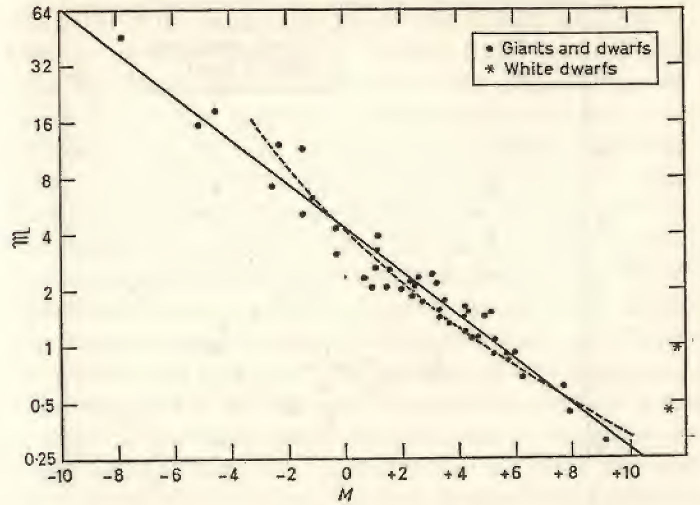


FIG. 4. Mass-Luminosity curve. The vertical scale is logarithmic and the masses are given in terms of the Sun's mass.

ordinates represent the masses of the various binary systems and single stars under consideration. The continuous line has been plotted following an empirical formula, derived from all these observational data, which links the mean mass $\mathfrak{M}$ with the mean absolute magnitude M:

$$\log \mathfrak{M}^{1/3} = -0{\cdot}04(M-5{\cdot}2)$$

The dotted curve represents Eddington's relationship and it can be seen that for the majority of the stars, the agreement could not be better. The only exception is the class of stars known as 'white dwarfs', which we shall discuss later. Actually the mass-luminosity relationship has been calibrated only with stars relatively near to us which belong to population I. For certain stars belonging to population II which are in a phase of contraction or of expansion, it is possible that the relationship may show some deviation.

Another diagram which is of interest is that showing the relation between mass and spectral class (fig. 5) which, as might be expected, resembles that linking luminosity and spectral class (fig. 8). We shall have the opportunity of discussing this when we come to deal with stellar evolution. The mass-luminosity relation shows that for a luminosity ratio of 10 to 1 we have a mass ratio of about 2 to 1.

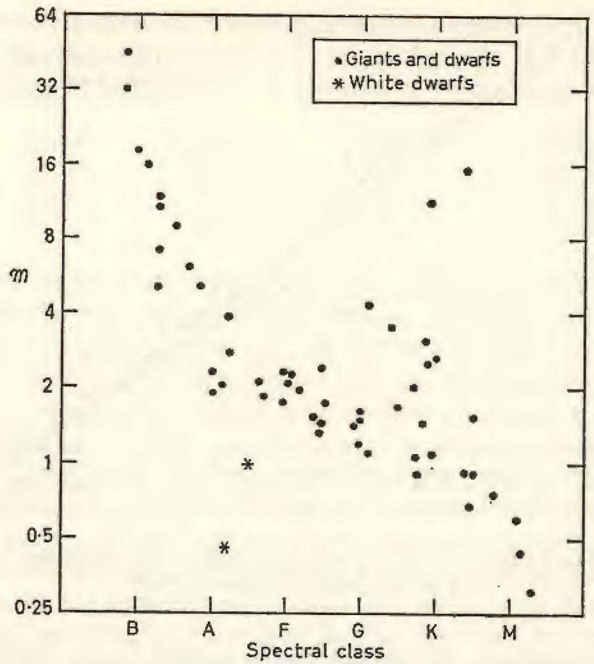


FIG. 5. Relation between mass and spectral class of stars.

Double stars are by no means exceptional among the stellar community, and this grouping of stars into physically connected systems must be accepted as a frequent and widespread feature of the stellar universe. We can therefore accept the results derived from the study of double stars as a complete picture of the magnitude and distribution of masses for the various types of stars.

In order to complete our survey of the physical characteristics of the stars we still have to review what is known about the volume and density of stars. The knowledge of these characteristics has enabled astronomers to develop theories regarding the internal constitution and the evolution of the stars. The volume of a star can be determined when its diameter is known. In the case of the Sun its diameter can be determined easily and with accuracy because the distance of the Sun from the Earth is known. Taking this as 93,005,000 miles, then the radius is 432,500 miles, or 109 times that of the Earth. The volume of the Sun is therefore 1,306,000 times that of the Earth; it follows that its mean density is about one quarter that of the Earth. Since the mean density of the Earth is 5·5 times that

of water, that of the Sun (taking the density of water as unity) is 1·4.

Owing to the great distances of the stars from us it is impossible to make direct telescopic measurements of the diameter of even the largest. But in 1919 it occurred to the physicist Michelson to combine an interferometer with a telescope, thus greatly increasing the resolving power of the latter. In this way it was possible to measure the diameters of some large and relatively near stars, to within about one-hundredth of a second of arc. This method was also used to measure the distance between the components of double stars when the components were too close together to be separated visually.

In its simplest form, the stellar interferometer consists of two slits which are mounted in front of the objective of a telescope, and the distance between the two slits can be varied by means of a micrometer screw. If a telescope, masked in this way, is pointed at a star, the rays emanating from each slit meet in the focal plane and produce a system of interference fringes. If the star is double, each component will produce its own system of fringes, and these will overlap to a greater or lesser extent, according as to whether the angle subtended by the two stars is equal to or different from the angle between a maximum and the adjacent minimum of the fringe pattern. When the two systems coincide exactly, the fringes will vanish. This happens when the angle subtended by the two components of the system is equal to the angle subtended by half the width of the fringe as seen from the objective. If λ is the effective wavelength of the light of the double star, and D is the distance between the slits, the angle is equal to $\lambda/2D$.

Suppose now that instead of a double star a single star is observed, and that its apparent angular diameter is within the resolving power of the telescope which is being used. The source of light may be regarded as being composed of a large number of adjacent light sources, each of which will form its own system of fringes. In this case, also, when the angular separation of the two furthest apart of these sources is equal to the angle subtended by the distance from the centre of the fringe system to the first dark band, the fringes will coincide and therefore disappear. The disc of a star, generally, is not equally bright, but is dimmer towards the limb on account of its own atmosphere, as is the case for the Sun. For practical purposes the disc of a star can be considered as divided into two half-discs, the total light from these appearing to originate in their centres. Thus a single star, which has a measurable apparent diameter, may be considered almost as a double star. Assuming a limb-darkening

similar to that of the Sun, the angular diameter of the star will be equal to $1{\cdot}43\ \lambda/D$. Since even in the most favourable cases, we are dealing with diameters of the order of a few hundredths of a second of arc, it is clear that objectives much larger than any in existence would be required to bring about the disappearance of the fringes. But it is possible to increase the aperture, as was done by Michelson and Pease with the Mt. Wilson 100-inch telescope, by means of secondary mirrors mounted at the extremities of an arm several yards in length, and fixed across the upper end of the telescope.

With such a device it has been possible to measure the diameters of several stars which other lines of investigation had already indicated as being exceptionally large. When the parallaxes of such stars are also known, their actual diameters can be calculated. These stars belong to the class of red giants, and one of them, α Orionis, appears to have a variable diameter. Perhaps it is a pulsating star, like those known as Cepheid variables which we shall discuss later.

The elements of the orbits of those double stars known as spectroscopic binaries and eclipsing binaries, can be deduced from their light-curves and their velocity-curves and hence the radii of the two components may then be derived. The radii so derived are about 10 times larger than that of the Sun in the case of class B stars, decreasing gradually to about 3 $\odot$ for those of class A, and $0{\cdot}6$ $\odot$ for the red dwarfs.

There are still other, indirect methods of determining stellar diameters. We have seen that if the stars are treated as perfect radiators, then there is a simple relation linking the absolute magnitude, temperature and radius of a star. If the first two quantities are known, then it is possible to calculate the third. Alternatively, the diameter can also be derived from the colour index i of the star, and apparent magnitude m, which are easier quantities to measure. Russell derived the following simple expression for d'', the diameter of a star expressed in seconds of arc:

$$\log d'' = 0{\cdot}82\, i - 0{\cdot}20\, m - 2{\cdot}52$$

This theoretical diameter, which is a function of the colour index and apparent magnitude, is valid only in the case of perfect radiators. In other words it can be applied, as an acceptable approximation, to the majority of the stars. Confirmation of the validity of the method is provided by the fact that its results are in good agreement with the stellar diameters obtained from direct measurements or derived from binary systems. Nevertheless we must remember that red giants

exist whose diameters are hundreds of times greater than that of the Sun, while dwarf stars of the same spectral class as the Sun have also about the same diameter (fig. 6). Finally there are the white dwarfs, the diameters of which are only a few hundredths of that of the Sun.

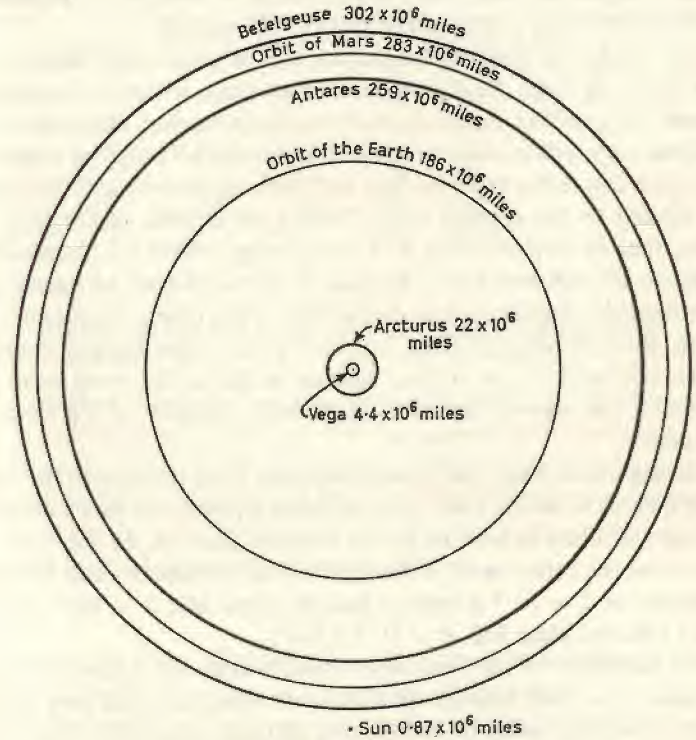


FIG. 6. Diameters of giants and dwarfs.

When we know the mass and the diameter of a star we can calculate its volume and hence its density, though there are only a few stars for which we have the requisite data.

The density of the components of binary systems, whether visual or eclipsing, is determined from the orbital elements of the system, in a manner similar to that already described in connection with the determination of the stellar mass. In the case of visual binaries, the semi-major axis and the period are not sufficient data for the determination of the density of the components, the ratio of the masses of the two components, and their luminosity in terms of that of the

Sun are also required. These can be obtained from the temperature of the star by means of Planck's equation.

In the case of eclipsing binaries it is possible to determine the mean density either of the system or that of the components. This can be done either by means of their light-curve which gives the radii of the components and from the knowledge of some of the elements of the orbit, or by means of the ratio of the masses.

The results of these investigations are of great importance, for they bring to light the fundamental fact that, whereas the stellar masses vary within relatively narrow limits, stellar densities, and volumes vary within much wider limits. Almost all eclipsing binaries are much less dense than the Sun and both the masses and densities are related to the spectral class. Taking the density of the Sun as unity, that of stars of class B is, on average, about 0·1, increasing to 0·3 in class A and to 0·5 in class F. Some systems of later type have densities similar to that of the Sun, while others are much less dense, their density reaching 2×10^{-6} g/cm³. The highest density yet encountered in one of these systems is that of the component of Castor, a red star of class M, which has a density of 2·6 that of the Sun.

Among dwarf stars, the density increases from the blue to the red, from a value of about 0·001 ⊙ it becomes equal to the Sun's density for stars of class G and 10 ⊙ for stars of class M. In the case of giants, on the other hand, α Aurigae which belongs to class G0 has a density of $2 = 10^{-3}$ g/cm³, α Scorpii, class M0, 3×10^{-7} g/cm³ and α Orionis, class M0, 6×10^{-7} g/cm³.

The densities of the few white dwarfs that are known, whose diameters are much smaller than those of other stars, are very much higher, reaching values from 20,000 to 300,000 times that of the Sun. The unusual properties of matter when subjected to such exceptional conditions have been at least partially explained by the advances in atomic physics and by investigations on the possible constitution of the stars.

In the table on page 79 are given some figures which refer to the physical characteristics of some giants, dwarfs and white dwarfs. These must not be accepted as more than approximate, since the measurements of some characteristics of some of the stars are still very uncertain. The letter *e* added to the spectral type indicates that in the spectrum of the star emission lines are present. Instead of the letters *g* and *d* which used to be prefixed to the spectral type to indicate giants and dwarfs, nowadays the following system suggested

by Morgan has been widely adopted. To the spectral class is added a Roman numeral from I to V. I corresponds to the supergiants, the following numerals refer to stars gradually less bright until we reach V which refers to dwarf stars. As an example: M2–I; G0–V; etc.

STAR	MAGNITUDE apparent	MAGNITUDE absolute	SPECTRAL CLASS	TEMP. °K	DIAMETER angular (″ arc)	DIAMETER linear ⊙=1	MASS ⊙=1	DENSITY g/cm³
α Scorpii	1·2	−3·0	*g* M0	3,100	0·042	300	15	3×10^{-7}
α Orionis	0·9	−2·9	*g* M0	3,100	0·048	350	15	3×10^{-7}
α Tauri	1·1	−0·1	*g* K5	3,300	0·034	50	4	2×10^{-6}
α Bootis	0·2	−0·3	*g* K0	4,100	0·023	25	4	3×10^{-4}
α Lyrae	0·1	0·6	A0	11,200	0·003	5	3	0·11
Krüger 60	9·2	11·2	*d* M3	3,300	0·0008	0·7	0·3	9
α Canis Majoris	8·4	11·2	F	7,500	0·0001	0·007	1·0	27,000

The data for α Scorpii and Krüger 60 refer to the primary component of the system in each case. Those for α Canis Majoris to the companion star (Sirius B).

In addition to density, another important datum for the theory of the constitution of a star and for the quantitative analysis of the spectrum of a star, is the acceleration at the surface due to gravity. That of the Sun, relative to the Earth, can be obtained approximately by dividing the ratio of their relative masses by the square of the ratio of their relative radii. Thus we obtain:

$$g \odot = 899 \text{ ft/s}^2$$

Therefore the force of gravity at the surface of the Sun is about 28 times greater than that at the surface of the Earth.

Our knowledge of the mass and radius of the stars allows us to derive the relation $g/g\odot$ where g is the acceleration due to gravity at the surface of the star, expressed in terms of that of the Sun.

Approximate values of $g/g\odot$ for stars of various spectral classes are tabulated below:

SPECTRAL CLASS	$g/g\odot$
B0	0·22
A0	0·55
d G0	0·85
d M0	1·2
g G0	0·034
g M0	0·002

CHAPTER VI

Rotation and Magnetic Fields of the Stars

Axial rotation and the existence of constant or variable magnetic fields are two characteristics which seem to be quite general among the heavenly bodies. We have an example of this in the Earth, which rotates in a period of 24 sidereal hours and has a well defined magnetic field. The Earth is a dipole with two magnetic poles which do not coincide with the rotational poles, nor are they diametrically opposite to one another. The lines of force of this field resemble those of a uniformly magnetized sphere (fig. 7), though they are less regular, converging towards secondary centres which can be considered as being almost subsidiary to the magnetic poles.

Instruments of various types allow us to determine the intensity

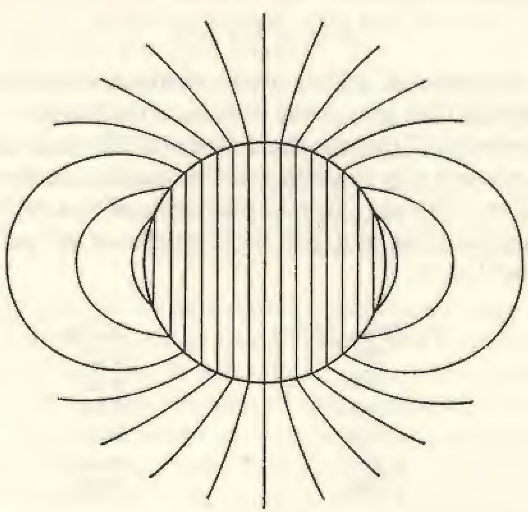


FIG. 7. Magnetic lines of force for a uniformly magnetized sphere.

Plate 6. Solar eclipse of 1961, February 15, photographed by Waldmeier at Passo della Consuma (Italy)

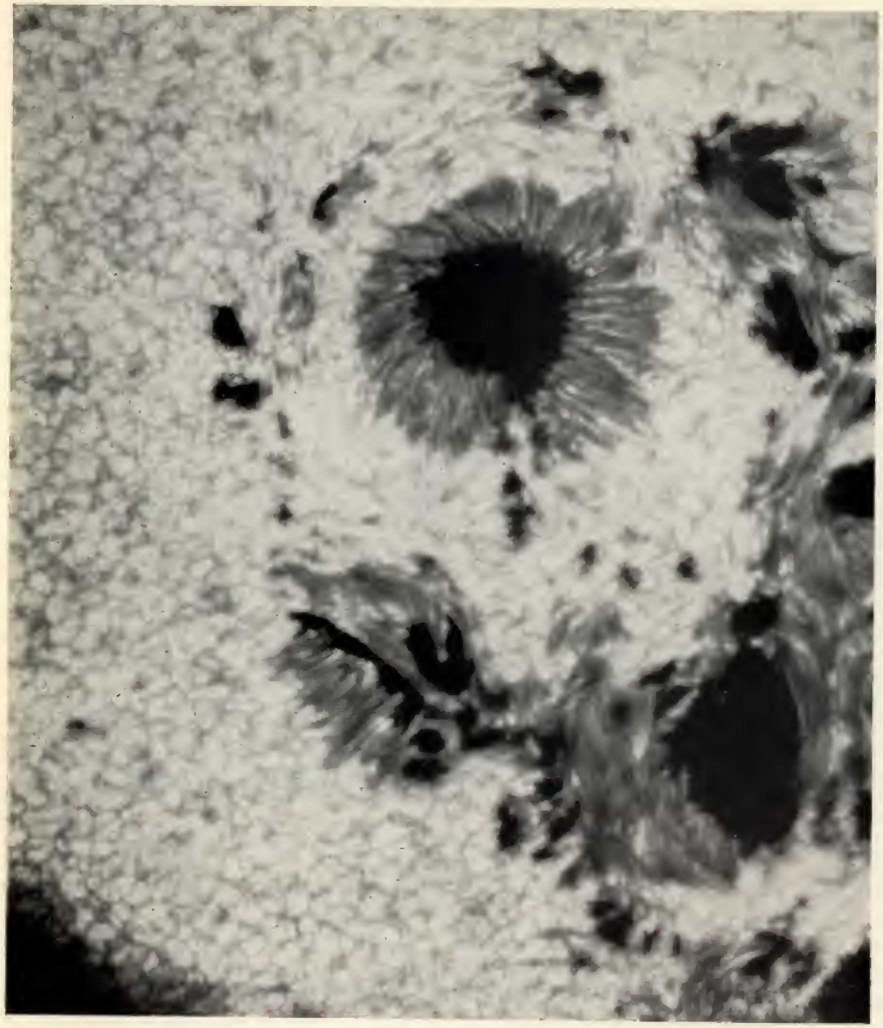


Plate 7. Sunspots: photograph taken by Stratoscope I. (Project Stratoscope, Princeton University, sponsored by NSF, ONR and NASA)

of the magnetic field of the Earth and its horizontal and vertical components at every point on the surface of the Earth, and in this way magnetic maps can be compiled which are invaluable to navigators as well as to investigators of terrestrial magnetism and of its variations. The magnetic field of the Earth is in fact subject to periodic variations, which can be divided into diurnal and seasonal fluctuations dependent upon the position of the Sun relative to the horizon at the place of observation. In addition there is an 11-year fluctuation dependent upon the activity of the solar cycle, and also long-period, or secular, variations which are probably connected with the origin of the terrestrial magnetism, concerning which various hypotheses have been proposed though the matter is still very uncertain.

If, as some recent theories suggest, the central nucleus of the Earth is fluid, perhaps a liquid metal of a high density and in motion and occupying half the volume of the Earth, then according to Bullard these conditions would explain the origin of the terrestrial magnetism and its secular variations.

Some light may perhaps be thrown on this very difficult problem by the study of the magnetic fields of the Sun and stars. The Sun, which is the nearest star to us, must be regarded as belonging to the G class of dwarf stars. It does not rotate as a solid body, but with a velocity which varies from the equator to the poles, though the mean value of its equatorial rotation is about 24·7 days. This period can be measured easily by timing the interval between two successive transits of a spot across the central meridian, or spectroscopically by using the Doppler effect, since the rotation of the Sun is causing its east limb to approach us while the west limb is receding. This rotational velocity amounts, at the equator, to about 1·2 miles per second.

It is not easy to prove that the stars, which do not present measurable discs, are rotating in the same manner as the Sun, although there are two methods whereby the rotation periods of certain stars can be determined. The first is applicable only to eclipsing binaries. At the time immediately preceding and following the total phase of the eclipse of the brighter component by the less bright, a narrow crescent of the former will alone be visible, and if the star is rotating it will be observed that the spectral lines are displaced towards the violet or the red according as to whether the visible limb of the star is approaching or receding from the observer.

The second method relies on the measurement of the broadening

of the spectral lines as a result of the star's rotation. If it is rotating, part of the visible surface will be approaching us and part receding, with the result that the two opposite Doppler displacements will be superimposed, and the lines will be broadened by an amount that depends upon the velocity of rotation. The first method is much the more reliable of the two, since the broadening of the spectral lines is influenced by the inclination of the rotation axis of the star to the line of sight as well as by other physical causes besides the Doppler effect.

The following table gives data of some eclipsing binaries, together with the velocity and period of rotation of the brighter component:

SYSTEM	SPECTRAL CLASS	ORBITAL PERIOD	BRIGHTER COMPONENT		
		(days)	Rotational velocity miles/sec.	Radius ⊙ = 1	Rotation period (days)
β Persei	B8	2·87	26·1	2·4	5·8
λ Tauri	B3	3·95	25·7	3·2	8·0
δ Librae	A0	2·33	39·1	2·9	4·8
RZ Cassiopeiae	A2	1·20	35·4	1·4	2·5

The shape of the solar corona, visible during total eclipses, had indicated that the Sun also has a magnetic field. When the activity of the Sun is low, that is when its surface shows few spots or other phenomena, the shape of the corona is typical of the lay-out of the lines of force around a magnetized sphere. This shape is modified to a greater or lesser extent when the Sun is active, particularly in the region of the poles of rotation which must therefore, as is the case of the Earth, be near to the magnetic poles. The coronal rays which can be seen are similar to the lines of force in the neighbourhood of the poles of a magnetized sphere (Plate 6).

The hypothesis that secondary magnetic fields may exist on the Sun was followed by Hale's discovery in 1908 that the sunspots are centres of such fields. Monochromatic photographs of the Sun obtained in Hα light, often show vortex-like formations of the hydrogen flocculi near the sunspots. These too are reminiscent of the distribution of lines of force around two magnetic poles of opposite sign which, in this case, are two sunspots belonging to one and the same group. This appearance suggested to Hale a method of proving the possible existence of magnetic fields in sunspots. The Mt. Wilson solar tower was built in order to obtain high dispersion spectra, and this enabled large-scale spectra of sunspots from the

red to the violet to be photographed. By using this solar tower combined with a suitable polarizing system placed on the slit of the spectrograph, Hale was able to prove the existence of the Zeeman effect in the spectrum of all sunspots. This effect consists in the splitting of the spectral lines into triplets or multiplets in the presence of a magnetic field, and Hale was able to determine both the intensity and the polarity of the magnetic fields producing the Zeeman effect in the spectra of sunspots. The intensity of the magnetic fields in different sunspots varies from a few hundred gauss to about 5,000 gauss, values which are much greater than that of the Earth's magnetic field which is only 0·6 gauss. These magnetic fields emerge, as it were, from the interior of the Sun with given polarities, which are opposite in the two hemispheres, and which undergo a general reversal between one 11-year cycle and the next. They are generated, as probably is the case for the Earth, by the convection motions of the gases. In the case of the Sun, these gases erupt from the interior, reaching the surface in a turbulent state.

As has been indicated, the shape of the corona had already provided a reason for supposing that the Sun, like the Earth, has a general magnetic field. This must in any case be fairly weak otherwise the Zeeman effect that it would produce in the spectra would be observed. Working on the assumption that the general magnetic field of the Sun is similar to that of the Earth, Hale and his collaborators in 1912 were able to show that such a Zeeman effect is in fact detectable. It appears as a slight broadening of the spectral lines in certain regions, selected on account of the assumed form of the lines of force. Since that time various other methods have also been used to demonstrate the existence of a general magnetic field on the Sun which has a variable intensity and the poles of which do not coincide with the rotational poles. Continuous observations which have been undertaken recently with a special magnetograph constructed by H. D. and H. W. Babcock, of the Mt. Wilson and Mt. Palomar Observatories, confirm the existence of a general dipolar field which has a mean intensity of about 2 gauss. The polarity of this field is opposite to that of the Earth and the field itself is normally restricted to solar latitudes higher than 60°, and is subject to irregular fluctuations both of intensity and of size. The polar magnetic fields have their origin in those very regions from which the polar rays of the corona, to which reference has already been made, appear to emerge.

It is highly likely that magnetic fields exist on the stars, as on

the Earth and on the Sun. Since stars do not present measurable diameters attempts had to be made to detect exceptionally intense general magnetic fields in those cases where the star's magnetic axis is parallel, or nearly parallel, to the line of sight. High temperature blue stars of the early classes (B, A, F), which have well defined metallic lines, are probably seen with their rotational axis pointing more or less towards the observer. On the other hand stars of the same types, which generally have the rotational axis pointing in a different direction, have the same metallic lines broadened by their rapid rotation.

H. W. Babcock was of the opinion that a Zeeman effect should be detectable in spectra of stars which had the rotational axis parallel to the line of sight. In 1946 he undertook his memorable research with the Mt. Wilson 100-inch reflector and a high dispersion spectrograph mounted at the lower end of the polar axis, below floor level. The light from the star was reflected from the 100-inch parabolic mirror to a hyperbolic mirror which increased the focal length and formed the image of the star on the slit of the spectrograph. In order to be able to detect the presence of a magnetic field, Babcock mounted a differential analyser in front of the slit. This produced two oppositely polarized spectra of the star, side by side on the photographic plate. On either side of these were recorded comparison spectra.

Among the first stars to be investigated with this apparatus was 78 Virginis and some of its spectral lines clearly showed relative displacements. The measured displacements can be exactly accounted for by assuming them to be the longitudinally observed Zeeman effect of a light source placed in a magnetic field having an intensity at the poles of 1,500 gauss. Even with a dispersion of 3 Å/mm these shifts amount to only 0·01 mm, and this makes us realize how difficult these determinations were and how accurate they have to be. Similar magnetic fields were detected in other stars, such as α Equulei, β Coronae and HD. 125248. The latter is a star in the constellation Virgo, of class A0, magnitude 5·7 with well defined metallic lines.

An important characteristic of these magnetic fields is that they are variable and moreover in the case of some stars the polarity of the magnetic field changes periodically. We have an example of this on the Sun between one 11-year cycle and the next. It should also be mentioned that on the star HD. 125248 marked variations of the intensity of the lines of ionized europium (EuII) and of neutral and ionized chromium (CrI and CrII) have been detected. These are in

opposite phase with one another and have a period of 9·3 days. The lines of neutral and ionized iron, on the other hand, maintain a fairly constant intensity. Together with the variation of intensity of these lines, the magnetic field also varies from +7,000 gauss when the EuII lines are at a maximum of intensity, to −6,200 gauss when the chromium lines are at a minimum of intensity. It appears that the reversal of polarity does not occur instantaneously in all the stars but rather with a rapid and progressive change related to latitude. In any case, the principal effects observed in the spectrum of this star can be explained by assuming the existence of a dipolar field, which is a general property of the star as in the case of the Sun.

Investigations on the magnetic fields of the stars carried out by Babcock, together with the spectroscopic investigations, lead us to the conclusion that stars which have intense magnetic fields have spectra in which the lines are exceptionally intense and which generally vary with the same periodicity as that of the magnetic field. Some stars of class A which have no magnetic field show spectral lines which are broadened because of the rotational effect. We can conclude therefore that a magnetic field exists and can be measured when we deal with some stars of class A which have narrow lines.

New hypotheses on the formation of the magnetic fields are replacing those which had led to the discovery of magnetic fields first in the Sun and later in the stars. So far the observations which can tell us something of the characteristics of the magnetic fields, as well as of the variation of the spectral lines and of the radial velocity with time, are very scarce. At present all we can say is that every star is a particular case. When an adequate number of observations is available it will be possible to formulate hypotheses and theories for many of the stars.

What we can say, so far, is that magnetic stars appear to have rotational velocities which are smaller than those appertaining to the average normal stars of spectral classes A and F. Moreover it is improbable that the axis of rotation of such stars is in the direction of the line of sight, because the variations in the spectra probably depend on the regions observed. Magnetic stars of spectral class A, belong to population I and are bluer than the normal stars. The exceptional intensity of some spectral lines, as for instance those of the rare-earth, points to a greater abundance of these elements which may be from a hundred to a thousand times as abundant as in

normal stars. This suggests some sort of difference in the chemical composition of such stars.

A detailed spectrophotometric analysis of the variable magnetic star α^2 Canum Venaticorum has been made by G. and E. Burbidge at the McDonald Observatory. This followed the discovery made by Babcock that this star has a magnetic field which varies periodically, with a period which is the same as that of the variation of its spectrum, with an amplitude from +5,000 gauss to −4,000 gauss. The equivalent width of 1,200 lines of its spectrum has been determined during the whole period. The star belongs to the class A0p, and is a typical example of the peculiar stars of class A having a variable spectrum. Its phase is of 5·5 days. The determination of its chemical composition, obtained by means of the curve of growth, shows that the rare-earth are very abundant, having an average ratio in relation to the Sun of 830. Deuterium is probably present, and lead is very abundant. The variations of the apparent great abundance of elements like titanium, chromium and iron have also been determined, and the conclusion reached is that some of these variations can be explained by movements and stratification of various levels during the magnetic period. It may be that the normal abundance can be explained by the nuclear reactions which take place at the surface of the star as a result of the acceleration of particles which is produced by the magnetic field dominant in the star.

The rapid variation of the magnetic field, in this as in some other stars, is probably closely linked with its period of rotation since the star is observed at various magnetic latitudes with consequent apparent variations of the magnetic field. The fact that the period of rotation coincides with the period of variation of the magnetic field as well as with that of the intensity and radial velocity of the spectral lines, seems to suggest that all these phenomena are due to the presence of large magnetic areas, as, on a much smaller scale, happens in the case of sunspots. It is in these areas that the increase in intensity of the various spectral lines is considered to take place.

CHAPTER VII

The Interior of the Stars — Stellar Energy

With the aid of thermodynamics, the quantum theory and atomic physics in general, theoretical astrophysicists have been able to provide a physical and mathematical picture of the internal constitution of the Sun and the stars. Although the theoretical results so far obtained are open to development and improvement, they have so far shown a remarkable agreement with the observations.

Stars are spheres of gas, and the problem is to investigate and possibly determine the conditions of pressure, density and temperature from their centre to their surface. We have already seen that it is possible to determine the temperature of stellar photospheres, and also, in the case of the Sun, the density distribution in its outer layers. The pressure, density and temperature increase progressively towards the centre of the star, and it is calculated that the central density must be about 50 times the mean density. From the weight of the overlying material, we can deduce that the central pressure must be of the order of a million tons per square inch, and the central temperature, assuming that the ordinary laws of gases are applicable, must be of the order of ten million degrees absolute. Unfortunately it is not possible in our laboratories to reproduce these temperatures, in order to investigate the behaviour of matter when subjected to such conditions. Nowadays it is possible, however, to establish in evacuated tubes a difference of potential which produces bombardments of atoms by electrons as violent as those produced by collisions occurring in a gas at a temperature of over a million million degrees. Temperature is no more than the expression of the mean kinetic energy of the molecules of the gas. At average terrestrial temperature, these have a velocity of some hundreds of yards per second, increasing to about 124 miles/sec. at a temperature of 50 million degrees, and free electrons attain a velocity comparable with that of light.

The conditions of the atoms in this state can give some information about what is happening in the interior of the Sun. In fact they must be so ionized as to have lost almost all their orbital electrons. From what we know of atomic structure and of the conditions that must prevail at the centre of the Sun, it would appear that atoms with a lower atomic number than 6 or 7 (carbon or nitrogen) must have lost all their electrons, thus being reduced to bare nuclei. Calcium atoms (atomic number 20) will have retained only their two innermost electrons, and iron (atomic number 26) only two or three. Eddington, by theoretical means, reached the important conclusion that matter, when as highly ionized as this, continues to behave as a 'perfect gas', since the volume occupied by the atoms stripped of their electrons and by the free electrons is always small in comparison with the total volume. At the same time, the atoms, although stripped of their electrons, retain their characteristic properties, because the collisions occurring in the interior of the Sun are not violent enough to transmute one element into another and therefore cannot deprive the nuclei of their identities. For this reason, when such atoms are removed to less extreme conditions they will recapture all the electrons they had before they were ionized.

Radiation laws indicate that the flux of energy within the Sun must be very great. This flux travels through the atoms; it is absorbed and re-emitted and slowly reaches the exterior of the Sun. In the presence of such energy, the radiation pressure, which is proportional to the fourth power of the temperature, will reach very high values and, being exerted in all directions, it will be mainly responsible for supporting the weight of the overlying layers. According to Eddington's calculations, in the interior of the Sun the radiation pressure amounts to 5% of the total pressure. The central density is 28 times that of water, the central pressure is 36 million atmospheres, and the temperature reaches 30 million degrees.

By means of a differential equation of the second order that is fundamental in thermodynamics, it is possible to calculate the pressure of the gas necessary to balance the force of gravity at any point within a gaseous sphere when the density is known as a function of the distance of the point in question from the centre of the sphere. Alternatively, if the density is known, the pressure can be calculated. In order to determine the distribution of the pressure and density, it is necessary to find another relation between these quantities. Emden, by comparison with analogous phenomena in the terrestrial troposphere, showed that this relation can be deduced from the theory of

adiabatic or convective equilibrium. For this it is possible to refer to a law which gives the required relation linking quite simply the pressure and the density. By means of this Emden was able to calculate the behaviour of the pressure and density in such systems which are known as 'polytropic spheres'. It is also necessary to know the mass and the radius of the star, and these, as we have already seen, are data which can, in special cases, be determined by various methods.

It soon appeared that the pressure of radiation must also be taken into account, with the result that the theory of radiative equilibrium replaced that of adiabatic equilibrium as a basis for the discussion. The theory of radiative equilibrium assumes that the internal energy of a star continuously produces as much heat as is dispersed into space. Eddington, basing his calculations upon the results of observations, discovered a remarkable relationship by means of which can be calculated the part played by the pressure of radiation in supporting the weight of the overlying layers, at every point in the interior of the star. If certain simplifying assumptions are made, this can be expressed as a function of the ratio of the mass of the star to that of the Sun, and of the mean molecular weight of the gas. Once the masses are known, the molecular weight can be calculated from the theory of ionization, given the pressure, density and chemical composition of the star. In this way it has been found that its value in the centre of a star is slightly greater than 2. Eddington was thus able to establish many relationships between the various physical characteristics of the stars, and with the help of the tables that Emden had already prepared, and which were also valid in his theory, he was also able to solve the problem of the distribution of density, pressure and temperature throughout the interior of a star. Among such theoretical relationships Eddington also calculated that which exists between the bolometric absolute magnitude, that is the magnitude corresponding to the total radiation in all wavelengths, and the mass of a star. The relationship between these two quantities is shown in figure 4. The dotted curve coincides with the continuous curve representing the mean of the observational data, when a suitable coefficient of opacity is adopted. We can conclude, therefore, that the relationship observed, between the mass and luminosity of a star with few exceptions, has been explained satisfactorily by the theory based upon general physical principles and upon that of radiative equilibrium.

As an example of all this, we can quote the results that have been

obtained for a giant and for a dwarf, Capella (α Aurigae) and Krüger 60 (that is No. 60 in the catalogue of Krüger which gives its position).

Capella is a spectroscopic binary which was discovered by Campbell in 1899. The two components do not differ greatly in luminosity, so that in their combined spectrum we can observe the lines of both components oscillating on either side of a mean position. This is the result of the Doppler effect produced by their orbital motion, which has a period of about 104 days. Since the system can also be observed visually with the interferometer, it is possible to derive not only its linear dimensions but also the individual masses of its components, and these are found to be respectively

$$\mathfrak{M}_1 = 4{\cdot}2 \qquad \mathfrak{M}_2 = 3{\cdot}3$$

Since the parallax of the star is also known, we can calculate the absolute bolometric magnitude of the principal component and this is $-0{\cdot}4$, that of the Sun being 4·9. It follows that Capella is 126 times more luminous than the Sun, and, its spectral class being G4, that its radius is 12 ⊙, and its mean density 2×10^{-3} ⊙. From Emden's tables, it can be calculated that its central density is 54 times its mean density. From the formulae of Eddington which take into account the pressure of radiation, and assuming its mean molecular weight to be 2·11, we find that the central temperature of the principal component is 9 million degrees and that the quantity of energy generated by a unit mass of the star in 1 second, namely the ratio between the intensity of its radiation and its mass, is 58 ergs/g.

Krüger 60 is a visual binary and the absolute bolometric magnitudes of the two components are 9·8 and 12·3. The components are red stars of class M, and therefore have an effective temperature of 3,100° K. From the elements of the orbit it can be calculated that the sum of the masses of the two components is 0·45 times that of the Sun (p. 71). The two masses can be derived indirectly from the absolute bolometric magnitudes by means of the mass-luminosity relation: $\mathfrak{M}_1 = 0{\cdot}35$: $\mathfrak{M}_2 = 0{\cdot}21$, giving a total mass of 0·56, which can be compared with the value obtained from observations. Although there is reason to believe that the discrepancy between these values may be real, and may be a characteristic of faint stars, nevertheless it may be concluded that the agreement between theory and observation is satisfactory. Theoretical considerations enable us to calculate the density of the system and it is found that the mean density of the system is 6·4 ⊙ and its central density about 350 ⊙.

It appears therefore that even at densities as high as this the laws of gases must still be valid. Furthermore, the central temperature of Krüger 60 is 32 million degrees, which is about equal to that of the Sun and of stars similar to it, namely dwarfs which, although they have widely different surface temperatures and central densities, yet have central temperatures which are of the same order.

At a temperature as high as this, which must be a function of the stage of evolution of the star, the atoms of its interior must be moving in all directions at high velocities. Besides these, there must exist free electrons and electromagnetic radiation of a wavelength comparable with that of X-rays. Free electrons will be captured by atoms which have lost their own electrons, but on account of the presence of the electromagnetic radiation, new collisions will be produced, thus setting up a rapid and continuous process. The atoms will be almost completely stripped of their electrons, and each will compensate for its smaller mass by a greater velocity and will rate as an atom in the production of the total pressure. The atoms and electrons, constantly re-combining and rapidly separating again, rebound in all directions in the interior of the star, but they are unable to reach the surface of the star on account of the force of gravitation. The electromagnetic waves, on the other hand, slowly work their way to the surface, being absorbed and re-emitted by the atoms with ever increasing wavelength. When they reach the outer layers of the star their wavelength will be partly within the visible spectrum, and can be observed by us as the radiation of the star.

The time required by this process is considered by theory as a coefficient of absorption, which may be compared with that actually observed in the quantity of radiation emitted by the star. We have already seen that the material of a star does in fact grow more opaque with increasing depth, but the comparison of theory with observation shows that a star absorbs much less than theory would suggest. This can be explained by the state of ionization of matter in the interior of a star. Even at the density of the heaviest elements there remains enough space between the ionized atoms in the interior of the star for the matter to be compressed to a density far exceeding anything attainable in the laboratory, though even in these conditions it still retains the characteristic properties of a gas. This explains how the important relation between mass and luminosity can exist in the stars.

In the different spectral classes, stellar energy manifests itself in the various colours of the stars, and these colours are directly related

to the surface temperature of the stars. It is precisely their surfaces, and the adjacent regions, which emit light and energy into space, and the gases of which they are composed are transparent only where their pressure and density are low. This external atmosphere, the photosphere of the star, is capable of absorbing radiation and forms the spectral lines, whose behaviour at various temperatures and pressures existing in those layers, we have already discussed. It is an undoubted triumph for the modern theories of physics that they have been able to shed some light on the constitution of the stars. At the same time the observation and, particularly, the spectroscopic analysis of the stars, provide us with experimental conditions of a kind that it is impossible to reproduce on the Earth.

It remains to consider how the Sun and the stars can produce and maintain a flow of energy as great and as apparently inexhaustible as that which they emit in all directions. This question has been a very difficult one to answer, because it was difficult to imagine a form of energy or a process which was capable of explaining the incredible length of time, both past and future, during which this flow of energy appears to remain constant, or virtually constant. Here also, the advance of atomic physics and, especially, the investigations of radioactivity and of the transmutation of the elements, have opened the door to a solution of the problem.

The geological study of the Earth's crust and of the radioactive processes which can be observed in it, indicate that the age of our planet must be of the order of 3 or 4 thousand million years. The Sun, during the same time, cannot have experienced any radical changes in the rate of energy that it produces. It is certain that there has been life on the Earth for the last 500 million years, and therefore during this interval of time at least, the Sun's heat, which makes life possible, must have remained the same, or very nearly the same, as it is now. The origin of the Sun's heat can nowadays be explained, thanks to the discovery of the mechanism whereby even so great a quantity of energy can be produced for periods of time of the order mentioned above. It is now some time since Helmholtz's theory had to be abandoned. According to this the emission of heat energy by the Sun and stars was the result of their gravitational contraction, but the length of time required by this process was very much too short. As a result of this, other theories were put forward to try to explain the much longer period of time during which the Sun and the stars had been radiating energy. One of these was based on radioactivity and it was necessary to suppose that the stars were

largely composed of uranium. This is not the case as observations show. Furthermore, radioactivity is incapable of explaining the radiation of the giants, which is thousands of times greater than that of the Sun.

The transmutation of elements, which has in recent times become possible in our laboratories, is probably the process which is going on ceaselessly in the interior of the stars and constitutes the source of their energy.

In this process, a small fraction of matter of the atomic nucleus is transformed into energy. It is a consequence of the theory of relativity that any change in a body's energy brings about a change in its mass. The equivalence of mass and energy as given by Einstein is:

$$E = mc^2$$

where c is the velocity of light in vacuum. Hence a loss of mass corresponds to the liberation of energy. Now a reduction of mass occurs whenever hydrogen is transformed into other elements, because its nucleus is much more massive than those of the elements following it in the periodic table and which may be thought of as consisting of ever increasing numbers of hydrogen atoms. Hence when electrons and protons combine to form an atom of some heavier element than hydrogen, energy corresponding to the loss of mass is liberated. This is the energy that maintains the radiation of the stars. Nuclear transmutations may be compared to chemical reactions. Neutrons and protons are analogous to the chemical elements, while nuclei are analogous to chemical compounds, and the transmutations consist of the exchange of neutrons and protons between two nuclei. This may result either from 'simple capture', when two nuclei, on encountering one another, simply combine, or by 'reaction', when the neutrons and protons of the nuclei in question do not combine to form a single nucleus, but distribute themselves between the two nuclei.

An example of simple capture is that of a proton captured by a lithium nucleus. These combine to form a nucleus of beryllium and the excess energy is transformed into a γ-ray, which is an electromagnetic wave of very high frequency. Alternatively, the combination of a lithium nucleus and a proton may give birth to two helium nuclei (α-particles), with the release of energy in the form of kinetic energy. This is an example of reaction, which in general is much more frequent than capture. Frequently, radioactive nuclei are

formed, which emit β-rays, that is electrons bearing either a negative or a positive charge. Examples of radioactive transformation are provided by carbon, the isotopes of which are capable of being transformed into boron and a positive β-particle, or into nitrogen and a negative β-particle.

Transmutation of elements is promoted in the laboratory by using high electrical potentials to accelerate particles until they possess very high kinetic energies. These give a proton a greater chance of penetrating, for example, the nucleus of a carbon atom and thus producing a transformation. But this is a rare occurrence, and happens only to a very few of the total number of protons involved. In most cases the protons are slowed down by collisions with atoms, and their energy is transformed into heat without producing any transmutations.

In the case of the stars the situation is very different. Because of the high internal temperature of the stars all the many protons are endowed with very great kinetic energies, which are not slowed down by reciprocal collisions since all the atoms have equally high energies. Therefore the energy produced is much greater, as it is not necessary to bombard the target with a large number of projectiles in order to obtain a single hit. Transmutations of elements in the stars are thus produced by very many nuclei having great kinetic energy, although it is lower than the energy which can be produced in our laboratories with very few nuclei.

What are the most probable nuclear transmutations which can occur in the stars? Bethe and other investigators of the various types of thermonuclear reactions capable of providing the large quantity of energy developed by the stars are in agreement that two types of reaction are the most probable, namely the 'carbon–nitrogen cycle' and the 'proton–proton chain'. It is now believed that the second reaction in which protons combine to form helium, with the emission of great quantities of energy, is primarily responsible for the production of energy in the Sun, while the carbon–nitrogen cycle is the more important in stars which are more luminous than the Sun. In any case, both reactions have the same result of converting hydrogen into helium. In the carbon–nitrogen cycle, carbon enters into the chain of reactions producing energy, and is then reconstituted. The process does not use up the nuclei of carbon, which, in any case, is not an abundant element on the Sun, and can therefore last for a long time. In other words, carbon acts as a catalyst. Bombarded by a proton, it is transformed into an isotope of nitrogen N13, which having a

half life of about 10 minutes becomes in its turn a stable isotope of carbon C13. This cannot be disintegrated by bombardment with protons, the only possible reaction being the capture of a proton, with the formation of N14, which is a stable nucleus. N14 can be transformed into O15, which is a nucleus with a half life of 2 minutes, after which it transforms into a stable N15 nucleus. This, in its turn, finally disintegrates with the formation of a C12 atom and an α-particle, namely an atom of helium as a result of proton bombardment.

The proton–proton chain reaction seems to unfold as follows. The initial reaction is the combination of two hydrogen nuclei, producing a nucleus of deuterium, H_1^2 and an electron. The deuterium nucleus then combines with one of hydrogen to give a nucleus of helium 3, He_2^3, and a γ-ray. In the third reaction, two nuclei of helium 3 combine, forming one nucleus of helium 4 and two of hydrogen. Thus also the proton–proton cycle leads to the conversion of hydrogen into helium and energy.

It is thus hydrogen, which is so abundant in the Sun and the stars, which provides the energy for these processes. The great quantity of hydrogen atoms which are present in the stars is thus responsible for the extremely long life of a star. These processes, which provide adequate quantities of energy, will continue until all the hydrogen is completely exhausted. Since the spectroscopic study of the outer layers of the Sun enables us to estimate the percentage of hydrogen of its content, we are able to predict that the life of the Sun will be 4 or 5 thousand million years.

The following table gives the absolute temperature necessary for the operation of the various thermonuclear reactions which occur on different types of celestial objects:

	°K
Bright nebulae	10^4
Surface of class O stars	3×10^4
Surface of the central stars of planetaries	10^5
Solar corona	10^6
Hydrogen thermonuclear reactions in the interior of the Sun	10^7
Helium thermonuclear reactions	10^8
Carbon thermonuclear reactions	5×10^8
Oxygen thermonuclear reactions; Interior of the hottest stars	$> 10^9$

For stars like the blue giants which emit more radiation and are more massive than the Sun, the carbon cycle develops further, with

an increase of temperature, since the fastest protons are able to penetrate more easily the region of electrical repulsion of the carbon nucleus. The increase of temperature that is found when we pass from the Sun to these stars, greatly accelerates the transmutations by a factor of 6,000 and this is in agreement with the observed radiation. The mechanism of energy production of other types of star, such as the red giants and the white dwarfs, must be a different one, which, so far, has not been elaborated.

CHAPTER VIII

Stellar Evolution

Soon after the first stellar distances were determined, it became evident that the apparent magnitudes of the stars, that is the measure of their apparent brightness, does not depend only upon their distance but also on their real luminosity. Thus Sirius (α Canis Majoris, apparent magnitude $-1{\cdot}6$), although the brightest star in the sky, appears to us much fainter than the Sun. In reality it is about 25 times more luminous than the Sun. Canopus (α Argus, apparent magnitude $-0{\cdot}9$) is next to Sirius in apparent brightness. It is very much more distant from the solar system and its intrinsic luminosity is found to be about 10,000 times greater than that of the Sun. Procyon (α Canis Minoris, $0^{m}{\cdot}5$), also one of the brightest stars, is 5 times more luminous than the Sun. On the other hand Rigel (β Orionis, $0^{m}{\cdot}3$), which is of almost the same brightness as Procyon and is of a bluish colour which indicates its very high temperature, and consequent very great surface luminosity, is intrinsically 10,000 times more luminous than the Sun. Betelgeuse (α Orionis, $0^{m}{\cdot}9$) is a red giant, and therefore of low surface luminosity, but since its diameter is 460 times that of the Sun, its real luminosity is 1,500 times that of the Sun.

We have seen that stars do not differ so much among themselves as regards their mass but that is not true as far as their density is concerned. Hence it is not quantity of matter, but rather the area of the radiating surface of the giant stars which is so much greater than that of the dwarfs. In other words, the volumes of the giants must be much greater than the volumes of the dwarfs. This we already know to be the case from the determinations of their respective diameters. The difference of luminosity and volume between the giants and the smallest dwarfs is the faintest component of the triple system which is the nearest known star to the Earth, namely α Centauri, at a

distance of only 4·3 light-years. This component, known as Proxima Centauri, is a class M star of apparent magnitude 11, and therefore of absolute magnitude 15·4.

About a dozen stars are known with real luminosity of this order, and we may therefore conclude that stellar luminosity ranges over a scale of from 1 to 200 million, and even more if we include novae which, as we shall see later, may at their maximum be a thousand times more luminous than even the most brilliant normal star.

In 1913, Russell drew a diagram (fig. 8) which included all stars

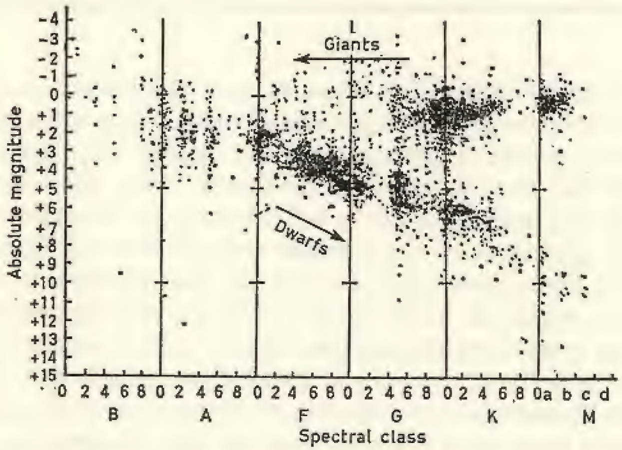


FIG. 8. The relation of absolute magnitude to spectral class (Russell Diagram).

of known parallax. In it the abscissae were the spectral classes from B to M, and the ordinates were the absolute magnitudes from -4 to $+14$. The resulting distribution of the plotted points was not as might have been expected, a random distribution, for the majority were concentrated in two zones. One extended diagonally downwards to the right of the diagram, from luminous, high temperature stars of classes B and A, to faint, M-type red stars. This branch was named the 'main sequence' by Eddington. To it belong our own Sun (class G0, absolute magnitude 4·8), Sirius, Procyon and Krüger 60. The second zone, consisting of very luminous stars, is distinct from the main sequence and is almost parallel to the spectral-type axis from the yellow stars to the red. Between these two branches, and also below the main sequence, are two large empty regions in which few or no stars are to be found. Bearing in mind the difficulty of obtaining accurate values of stellar parallaxes, especially in the case

of the more distant stars, it was at first suggested that the particular distribution exhibited by the diagram might not be real, but rather due to the selection of the observed stars. The many more accurate determinations of stellar distances that were made subsequently, including, as we shall see later, the spectroscopic parallaxes, progressively confirmed this characteristic distribution of the brighter stars and of the main sequence, with few stars occurring between the two branches.

Hertzsprung suggested the name giants for the former and dwarfs for the latter, a nomenclature which has been universally adopted. It can be seen from the diagram that whereas the giants do not differ greatly among themselves as regards brightness, the dwarfs become increasingly faint with increasing redness. For this reason, the separation between giants and dwarfs only begins to be marked after class F. The difference between them is greatest in class M, so that there are stars which differ, on the average, by about 9 magnitudes, but have spectra which appear very similar. In the lower left-hand corner of figure 8 (see also fig. 4, p. 73) are to be found a few stars which, since they are dwarfs and belong to the first spectral classes, are known as 'white dwarfs'. We have seen that the physical characteristic which varies most widely among the stars is density. It is very low in the giants, increases steadily towards the dwarfs, and attains its greatest value in the white dwarfs.

Theoretical considerations lead to the conclusion that the material of which the stars are made continues to behave as a perfect gas even at the greatest densities. As the conditions prevailing in the stars are so different from those encountered on the Earth, there is no reason why the density of the dwarfs should not be even greater. It had been noticed for some time that some stars have spectra which do not exactly fit their real brightness and which must therefore be regarded as exceptions. The study of these stars has been of the greatest interest.

Sirius is not a single star but a visual binary with a small companion which lies at a distance of 10″, having an apparent magnitude of 8·4 and a mass, as derived from the elements of its orbit, of about 0·8 times that of the Sun. The absolute magnitude of this component is 11·3, corresponding to a brightness of 0·003 times that of the Sun. If it were a red star of the more advanced spectral type it would not be an exceptional example of a dwarf star. Its spectrum is difficult to observe with telescopes and spectroscopes of moderate size owing to the brilliance of its main companion which is 10 magnitudes

brighter. In 1914, however, Adams discovered that its spectrum is that of a white star. To be exact, its spectral class is F0, while that of Sirius is A0. Assuming that the companion of Sirius may be treated as a black body, then its surface temperature of 8,000° K (that of class F stars) and its absolute magnitude of 11·3 indicate that its radius is about 11,185 miles. Thus although its mass is only slightly inferior to that of the Sun, its size is incomparably smaller. Its volume is only $\frac{1}{50,000}$ that of the Sun, and therefore its density must be equal to 60,000 times that of water. Since then, other stars of this type have been discovered, as for instance, van Maanen's star, which has an apparent magnitude of 12·6 and an absolute magnitude of 14·5. This star is of spectral class F, has a radius 0·007 times that of the Sun and a density 400,000 times that of water.

As long as it remained impossible to imagine the condition of matter in the interior of the stars, these results appeared to be absurd, although they were based on well established data and were moreover confirmed by independent methods. The suspicion that the spectrum of the smaller companion of Sirius might be formed solely of the reflected light of the primary was proved to be unfounded by the discovery of other equally exceptional stars. According to modern physics, it is possible that the atomic nuclei in the interior of the stars may be stripped of their shells of electrons. This would explain how the constituent gases of a star may be compressed to enormous densities while still having enough space around them to be able to move, so that matter in the interior of a star can still be considered as gaseous.

In any case, independent confirmation of these results was desirable. This was brilliantly and decisively achieved by means of the theory of relativity. It is well known that according to this, the wavelength of light emitted in a gravitational field will appear to an external observer to be lengthened, so that the absorption lines in the spectrum of the Sun, or of a star of considerable mass, will appear to be displaced towards the red. This is the so-called 'Einstein effect', a shift of the spectral lines towards the red by an amount which is proportional to the mass of the star divided by its radius. In the case of the Sun, theory predicts a displacement amounting to only a few thousandths of an Ångström. Interpreted as a velocity shift (Doppler effect) this would be equivalent to a velocity of 0·4 miles/sec. The existence of this effect appears to have been established, although the proof is not easy in the case of the Sun, owing to the smallness of the effect, which is close to the limit of the errors of observation and

also to the fact that it is masked by other similar small displacements. In the case of the companion of Sirius, since its mass is about equal to that of the Sun whereas its radius is very small, the effect will be 31 times greater than on the Sun. The consequent red shift equivalent to 12 miles/sec. should be easily measurable if it could be disentangled from the true Doppler effect caused by the radial velocity of the star. Since the radial velocity can be determined, knowing that of Sirius and the radial component of the orbital motion, the verification was carried out.

A powerful instrument was required for this investigation because owing to the great quantity of light emitted by Sirius, that of its nearby companion is almost completely effaced. In 1925, Adams succeeded in photographing its spectrum with the 100-inch reflector at Mt. Wilson, and measurements of the displacements of some of the hydrogen lines of the Balmer series indicated a mean Einstein shift towards the red which was equivalent to 12 miles/sec., in perfect agreement with the prediction of theory. Thus Adams' observation not only confirmed one of the predictions of the theory of general relativity, but also proved the existence in the universe of matter in a state of compression far exceeding that of the densest terrestrial elements.

It is certain that white dwarfs exist in greater numbers than have so far been detected (about 75 up to 1950), but, owing to their faintness, it will be realized that their discovery is not an easy matter unless they are in the immediate vicinity of the solar system. These white stars must be regarded as exceptions to the stellar sequence, and it can in fact be seen from the mass-luminosity diagram or the spectral type-absolute magnitude diagram that they do not behave like the rest of the stars. This may be because the laws of gases are no longer valid in the case of the white dwarfs, as Eddington suggested, or may be due to an increase of the coefficient of absorption produced by the accumulation of ions and electrons. The problem now arises, whether to place these stars at the beginning or the end of the process of stellar evolution.

In the meantime, let us see how it is possible to group the majority of the stars according to their brightness. It can be seen from the diagram that three main classes may be distinguished, namely dwarfs, giants and those still larger stars to which the name 'supergiants' has been given. The separation between the first two classes is greatest among the low-temperature stars, and diminishes steadily as the temperature rises, since the luminosity of the dwarfs increases while

that of the giants slowly decreases. Among the supergiants there are stars of great brightness which have a much wider range than that existing for the giants and the dwarfs. Many of them are variables and this, together with their remarkable dimensions and high rate of radiation indicates that a sort of instability may be inherent in these stars.

It is a characteristic of both giants and dwarfs that they tend to group themselves round definite magnitudes. In other words, the majority of the stars of a given temperature are able to emit a given quantity of energy, and hence they can have a real luminosity without appreciable dispersion. The brightness of those giants which have a temperature lower than that of the Sun, ranges from 100 ⊙ to 150 ⊙ and varies only slowly as the temperature decreases, while it increases slowly in the case of the cooler giants. This is due to the large dimensions of these stars, for the increase in the area which emits the radiation more than compensates for the slight reduction in brightness of its unit area. In the case of faint stars, the variation of luminosity with temperature is rapid. A decrease in temperature results in a steady decrease of luminosity which becomes very sudden in the case of cooler stars. Dwarfs are relatively small and dense bodies, and the lower their temperature, the smaller their mass and the greater their density. Here there is no increase in size, as there was with the giants, to counterbalance the effect of reduced surface brightness due to reduced temperature.

Although these results have been obtained for a limited number of stars, which can be assumed, more or less, to represent the present conditions of the universe in the neighbourhood of the solar system, it is natural to use them as a starting-point from which to search for a possible evolutionary process of the stars based on the Russell diagram, the mass-luminosity diagram and the hypothetical conditions of stellar interiors.

Lockyer, in his day, even without knowledge of the most recent observations, had shown that it is possible to distinguish relatively young stars, the temperature of which is increasing, from relatively old stars the temperature of which is decreasing. Later Russell, by means of the spectral class-absolute magnitude diagram, showed that the giants and dwarfs exhibit these very characteristics of increasing and decreasing temperature. Thus stars could be thought as starting their lives by becoming visible as low-temperature, class M giants, and evolving gradually until they attain their maximum temperature in classes A and B, when they start to cool and pass down the main sequence branch.

According to the theory which, as we have said, has had to be abandoned, that the stars derive their energy from gravitational contraction, the interior of a contracting star should become ever hotter until its density becomes so high that the laws of gases can no longer be applied to it. Its general temperature will reach a maximum value and then begin to decrease until the star, which is further contracting, will no longer be able to radiate as a luminous body, passing into the liquid or solid state. According to this hypothesis, and in agreement with the Russell diagram, the stars born from a nebula or from a gaseous condensation of great size and low surface temperature, suffer a considerable degree of contraction, becoming ever hotter until the gas in their interior reaches a critical density and their surface a maximum temperature, after which the phase of cooling will set in.

We now know from the properties of gases, the mass-luminosity relation and the new concepts that have had to be introduced to explain the origin of stellar energy, that this hypothesis is not tenable. Alternatives have therefore had to be sought, and these are still being continually developed and improved. If it is assumed that the source of energy is to be found within the interior of the star, and that the energy is liberated gradually, leading to a steady increase in the internal temperature of the star, then we have to find the conditions under which this process can occur without catastrophic results, such as an explosion of the star.

Since stars are simply spheres of gas, if more heat is generated than can be radiated from its surface it will expand, with consequent cooling of its interior and slowing down of the processes generating the energy. When a certain stage of cooling has been reached, a general contraction of the star will set in, and the production of heat will recommence. Such a cyclic process provides conditions of equilibrium, whereby the quantity of heat radiated from the surface is matched by that generated internally. The dimensions of the star are thus automatically stabilized by the radiation of energy from the surface, which is in equilibrium with that produced in its interior. The nuclear reactions which are capable of liberating large quantities of energy could in fact be started by collisions no more violent than those which can actually occur in the interior of the stars.

It will no doubt be possible to predict the course of stellar evolution when the laws regulating the production of subatomic energy are known. At the moment this prediction is not possible and we must therefore accept the limitations of what we can actually observe.

Let us assume that the quantity of energy produced varies with the temperature, density and composition of the gases, and that it differs at various points within the interior of the star. On this basis it is possible to calculate different theoretical models in which the energy produced is equal to that radiated from the surface of the star. The star will then be in equilibrium, neither its temperature nor its size varying. It has been found that a star of a given mass and chemical composition will in general only be in equilibrium for a single value of its radius, and hence for determined values of its luminosity and surface temperature. If the mass alters, these values will also change, but so long as the chemical composition is the same, all stars of a given luminosity must have a given magnitude, surface temperature and spectral class. A star therefore, considered as a gaseous sphere in equilibrium under the action of gravity and of the pressure of the gas and the pressure of radiation, must have a radius, surface temperature and luminosity which are determined by its mass and by its chemical composition. Eddington's mass-luminosity relation is a particular case of this general result, which was established by Vogt in 1926. From this can be derived a diagram similar to that linking the luminosity of a star and its spectral type or temperature.

If the chemical composition of all stars were the same, the points on this diagram should, within the limits of observational errors, lie on a straight line. Since this is not the case, we must assume that the composition of all the stars is not uniform. We have already learnt what are the relative abundances of the different atoms on the Sun; if this is different in other stars, their mean molecular weight will vary widely, as also will their opacity and the quantity of energy that they release per unit time. By varying the hydrogen content, for example, it is possible to make very different luminosities correspond to a given mass. If the proportion of hydrogen is increased, the reduction of the mean molecular weight will compensate for the reduction of opacity, so that of two equally massive stars, that which is richer in hydrogen will be the less bright.

Thus by assuming that the hydrogen content of the stars may not be constant we have cleared the way for a possible explanation of the Russell diagram. For a given value of the abundance of hydrogen, we can calculate the surface temperature for different values of the mass and make a diagram similar to Russell's. All points lying on a straight line represent stars with the same hydrogen content. We shall thus obtain a diagram consisting of a series of curves indicating the course of the evolution of all the stars according to the quantity

of hydrogen that they contained at the time of their birth as individual bodies. In order to obtain some sort of resemblance to the Russell diagram it is necessary to assume that the hydrogen content of the majority of the stars lies between 15% and 45%. It seems that stars with the highest temperature, such as those belonging to classes B and A, can only be stable if the percentage of hydrogen is very high, from 30 to 40%. This would be the case with the Cepheids and other variables, which are very bright stars of large mass.

Abundance of hydrogen and size of mass are therefore the factors on which the characteristic distribution of the Russell diagram depends. The regions of this diagram in which the stars are found represent comparatively stable conditions, under which stars can exist for a relatively long time and this is the case with the main sequence. The white dwarfs are an exception, being separated from all the other stars both in Russell's diagram and in the mass-luminosity diagram and we must therefore suppose that their constitution differs from that of the other stars, as in fact is indicated by their great densities. The greater part of their mass is believed to consist of 'degenerate gas' and it can be shown that under these conditions a body would have a definite size which is determined solely by its mass and composition. In it, the sources of energy common to other stars must be almost completely exhausted or incapable of functioning. The outer layers, which are not degenerate, will become ever thinner until with continued contraction and cooling, the star ceases to be luminous altogether.

Many points concerning the evolution of the stars still remain to be clarified. Probably it is not correct to regard the main sequence and the giants' sequence as representing the actual course of evolution, in the sense that all stars must pass through all the stages shown in the Russell diagram. For this to happen the differences of mass should be less marked. The various stages that the stars have reached should be considered as representing particular conditions that they have reached in the course of their development, conditions in which the majority of the stars are to be found at present and which most of them will maintain.

It must be noted that the Russell diagram is incapable of giving a true picture of the distribution and frequency of stars of different types as a function of their brightness. The diagram embodies an effect of selection in that the stars plotted on it are at various distances from us. But this diagram is mainly based on the determination of distances whether by means of the trigonometric or

spectroscopic parallax. In fact one of the axes represents absolute magnitude, the determination of which requires a knowledge of the distance or parallax of the star. Now it can be seen that in the diagram stars are plotted down to about the 9th magnitude, and it is obvious that stars with greater intrinsic luminosity will be more distant than those which are faint. A true comparison of their frequency can only be made when their numbers are reduced to unit volume of space. When this is done it is found that the Russell diagram assumes a modified form. The giants and supergiants become extremely rare by comparison with dwarfs, and so do stars of classes O and B. The dwarfs, on the other hand, are more common as we advance in the spectral classification. White dwarfs are also numerous, making up 10% of the stellar population in the neighbourhood of the Sun.

It thus appears that the Russell diagram gives a true picture of the distribution of the absolute magnitudes in the different spectral types only in the neighbourhood of the Sun, that is in a region of the Galaxy which is rather remote from its centre, and, situated, as is nowadays believed, in one of its spiral arms.

The study of globular clusters and galaxies with powerful instruments, which are capable of resolving the regions close to their nuclei

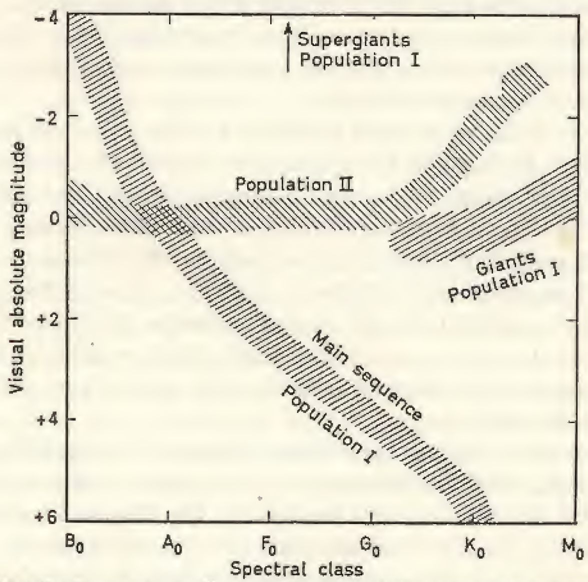


FIG. 9. Distribution of stars of populations I and II according to their absolute magnitude and their spectral class.

into stars, has in a sense completed the Russell diagram. In our own Galaxy unfortunately this is not possible on account of the interstellar matter which prevents us from seeing the centre.

Examining photographs, particularly of the Andromeda Nebula, taken with the Mt. Wilson and Mt. Palomar telescopes with red and blue sensitive emulsions, Baade noticed that blue supergiants of classes O and B were absent from the central regions of this system, while the red giants more luminous than those which appear in the classical Russell diagram were abundant. A similar characteristic was shown by the globular clusters. If the stars which have these characteristics are plotted on the Russell diagram, it is found that they do not fall within either of the two branches, but occupy the positions shown in figure 9. Baade therefore suggested that stars which have these characteristics should be divided into two separate stellar populations. Population I occupies the zones already familiar in the classical Russell diagram, population II is that which occupies the new zones, and is characterized by stars found in the neighbourhood of the nuclei of galaxies or in the globular clusters (Plate 8).

The characteristics of the two populations are as follows:

Population I Blue supergiants, the most luminous of which have visual absolute magnitudes up to -7 (that is 10^5 times as bright as the Sun); classical Cepheids; double stars; all stars situated in the arms of spiral galaxies, together with interstellar matter.

Population II Red giants, the most luminous of which have visual absolute magnitudes up to -2 (that is 10^3 times as bright as the Sun); variables of the type RR Lyrae, RV Tauri, W Virginis; stars which are found crowded together near to, or within, the nuclei of spiral galaxies and in globular clusters.

It will be seen that whereas in some regions of the diagram the two populations are quite distinct, in others such as those for the giants of classes G, B and A, there is no clear-cut distinction between the two populations. This may lead us to conclude that they are the result of stellar evolution along different lines of development, due to the varying chemical composition of the stars in their formation period. According to Strömgren, we may assume that after a relatively short phase of contraction, the stars achieve a state of equilibrium at a temperature which is so high that the energy produced is exactly balanced by that radiated. During this phase, the properties of a star are determined by its mass and its chemical composition.

As a consequence of the transmutation of hydrogen into helium, as evolution proceeds slowly or rapidly, changes will occur in the chemical composition of the various stars, though their masses will remain virtually constant. When the hydrogen is completely exhausted, the star will once again start to contract, and will perhaps end up as a white dwarf if its mass is small enough.

Further investigations seem to point to the fact that in reality it is not simply a question of the existence of only two well defined populations as suggested in the original work by Baade. From population II to population I the transition is gradual and consists of several steps of a well defined evolution, which depends on the gradual burning of the hydrogen which originally was present in the star. From the oldest stars of population II, perhaps seven or eight thousand million years old, which are represented in the Galaxy in the globular clusters and individual stars which have broken loose from these clusters, there is a transition to an intermediate population which in the Galaxy occupies a volume which is not completely spherical, being slightly flattened. To this group belong novae and the planetary nebulae.

On the disc of the Galaxy exist stars from three to five thousand million years old, which form its centre. The Sun can well belong to this group on account of its chemical composition.

From this group we pass to an intermediate group which bears more resemblance to population I and which contains stars with an age ranging from a hundred to a few million years. According to these views Sirius would belong to this group which lies near or in the central plane of the Galaxy. Finally we reach stars of population I having an age of ten million years or perhaps even less. These stars are mixed with gas and cosmic dust which have not yet condensed. Both gas and stars are situated in the spiral arms of our Galaxy, as for example Rigel and the stars in the Orion Nebula.

It is obvious that this division is purely conventional, and that in actual fact the transition from one type to the other is very gradual.

The chemical composition of the various types actually justifies this hypothesis. In fact in stars belonging to globular clusters, heavy elements which were formed with the gradual burning of hydrogen are rather scarce.

The knowledge of the abundance of the different elements in the various types of stars is one of the most important factors in the explanation of the formation and evolution of the star. From the information so far available, Struve gives the following comparison

of the abundance of certain elements in the universe, in young and in old stars:

Element	*Abundance in the universe* %	*Abundance in young stars* %	*Abundance in old stars* %
Hydrogen	75·5	58·6	0
Helium	23·3	39·8	95·4
Carbon	0·080	0·10	0·31
Nitrogen	0·17	0·17	0·47
Oxygen	0·65	0·48	0·75
Neon	0·32	0·73	3·00
Silicon	0·053	0·08	0·065

Only with fuller information and more detailed study of the effects in the spectrum due to the chemical evolution of a star, will it be possible to solve the problems relating to stellar evolution.

CHAPTER IX

Systems of Stars — Double and Multiple Stars

If the stars, despite the diversity of their sizes and characteristics, are to be considered similar to our Sun, then we must also consider the possibility that some among them may be accompanied by families of planets. On account of their great distances these would be invisible to us, the stars appearing to be isolated and independent of one another. The fact that the distribution of the stars over the face of the sky is extremely uneven, suggests that there may exist systems of stars which belong to a single family, even though their mutual separations may be relatively great. This is confirmed by the study of their proper motion. Examples of such systems of stars are the Galaxy itself, and the globular and open clusters. The globular cluster is a group of stars with star density increasing towards the centre, and the open cluster is a group of stars animated by a common proper motion.

When a powerful telescope is used, it is frequently noticed that two or more stars are apparently very close together, forming what is known as a double or multiple star. This may of course be nothing more than an optical effect because the stars, in reality, may be very distant from one another, but they may just happen to lie almost on the same line of sight. Such systems are termed 'optical doubles'. If, on the other hand, there is an actual physical connexion between the two stars, they are known as 'physical doubles' or 'binaries'. The existence of such systems which are more common than optical doubles was first established by Riccioli in 1650. If the telescope eye-piece is fitted with a micrometer consisting of movable wires, controlled by micrometer screws, it is possible to measure the relative position of the two components at suitable intervals, usually a period

of several years. From these measurements it is found that the components of a binary system appear to revolve around each other. This motion obeys the same laws that control the solar system, so that the two stars must be subject to a mutual attraction under the influence of universal gravitation. The two components of a binary system, therefore, move around their common centre of gravity. It is possible that one or both components of these systems may have companion stars of their own, whether visible or invisible, and the existence of these can be proved by various observational and theoretical methods.

Since the distance separating the components of a double star is very much smaller than that separating the individual stars in the sky, it will be obvious that the chance of discovering such systems will increase with the instrumental power employed. We have already seen that the possibility of separating a double star depends upon the resolving power of the telescope used (p. 29). With modern interferometric methods we can reach angular separations of the order of the angular diameters of the stars, namely a few hundredths of a second of arc. In general, therefore, only systems relatively near to us can be directly observed with a telescope; that is when they are within a few dozen parsecs from us, and provided that the distance between the components is not too small.

There is still another difficulty which restricts the discovery and observation of visual binary systems. If the two components are of about the same brightness, they can be seen individually provided their angular separation is equal to, or larger than, the resolving power of the instrument. If, however, one component is much fainter than the other it often happens that its light is effaced by its more brilliant neighbour. However there are two further methods whereby binary systems can be detected even though their components cannot be separated visually. One is the spectroscopic method, by means of the observation of a Doppler effect due to the motions of the components along the line of sight, and the other is a photometric method. This is based on the observation of the variation of brightness of the system, which reveals that a star appearing as single must be, in reality, a double and that the periodic variation of light must be due to the fact that the components eclipse one another in the course of their orbital motion. Thus we have introduced two additional classes of binary stars, the 'spectroscopic binaries' and the 'eclipsing binaries'.

VISUAL BINARIES

Let us first discuss the visual binaries. It must be recalled that the long and patient measurements, made since the time of the Herschels and the Struves with ever more powerful instruments, have led to the discovery of many double stars and also of a few multiple systems. New discoveries continue to be made all the time and the number of such known systems has increased accordingly. The measurements are made with a micrometer, and generally consist of the determination of the polar co-ordinates of the fainter star referred to the brighter.

In more recent years photography has been used, but this cannot compete with the visual method when the components are very close together, since the photograph is taken at the prime focus of the telescope without any enlargement. Photography, however, has the advantage of giving an increased accuracy in the case of systems when the components are sufficiently distant from one another. Another of its advantages is that it reduces the 'magnitude error' which usually arises when we try to relate a bright component to another several magnitudes fainter. To eliminate this error, it is usual in the photographic measurement of double stars to mount a low frequency 'grating' in front of the telescope objective. This grating, consisting of suitably spaced wires, gives a direct image of a star accompanied by spectra in the first, second, etc., orders. In practice, owing to the low frequency of the grating, the intensity of the successive images decreases in a known proportion. Thus we can compare, for example, the first or second order image of the brighter component with the direct image of the fainter component and in this way eliminate, to a large extent, the magnitude error.

Measurements repeated over a succession of years reveal the motion of one component relative to the other, and also the type of motion. Only in the case of about two hundred, of all the double stars known, has it been possible to prove the existence of true orbital motion. In the case of the others, either the period covered by the observations is too short to reveal it, or we are concerned with the relative motions of stars which appear to be near to one another only because of an optical effect. In the latter case, however, the observed motion can be used to determine the proper motion of the brighter stars, which generally are nearer to us. In this way the relative proper motion of the brighter stars with reference to the

faint stars can be determined with great accuracy, and such determinations are very important for the statistical study of the stellar distances and motions.

When after repeated observations over a certain period of time, it is established that one component is apparently revolving around the other, the problem which remains to be solved is to determine the orbit which best fits the observations as a whole. This orbit can be obtained by either graphical or analytical methods. The starting-point is that according to the law of universal gravitation and the rules of projective geometry the real orbit in space is, like the apparent orbit observed, an ellipse. In visual systems the motion is generally slow. The most rapidly moving of these systems complete one revolution in a few years, while the slowest require several centuries.

The apparent orbit will be that which fits most closely all the available observations. Measurements of the positions of double stars have been made for little more than a century, and a slow-moving binary will in this time have completed an arc of its orbit which is too small for the whole of the apparent orbit to be established, hence only an approximate solution can be derived. Once the apparent ellipse has been derived by graphical or analytical methods, we can calculate the elements defining the shape and size of the true orbit, as well as the plane in which it lies, and the position, at any given moment, of the companion star relative to the primary. It is not possible from micrometer measurements alone to determine on which side of the plane of projection, taken as reference plane, the companion lies at a given time. In other words, it is impossible to distinguish between the ascending and the descending node unless other types of observations are available.

Although the number of double stars for which orbits have been established in this way is a small percentage of the total number observed, the theory of probability shows that a very large percentage of these must be binaries, rather than optical doubles. The mathematical probability of the occurrence of very close doubles among a random distribution of stars up to a given magnitude is much smaller than the number of already known doubles of various brightness. Hence a large proportion of these must be physical binaries.

The periods of those double stars whose orbits have been well established, range from approximately two years to several centuries. About a dozen have periods of less than 25 years, and fifty have periods of from 25 to 100 years. As we have already said, double

stars with periods longer than this cannot have been sufficiently observed therefore their orbits can only be known approximately.

The orientation of the orbital planes in space do not show a preference for any particular direction. Their eccentricities, unlike those of planetary orbits, are generally high. The mean angular separation of the two components of binary systems range from $0''\cdot1$, which is close to the resolving power of existing telescopes, to about $20''$ (α Centauri), with a greater frequency for angular separations around $2''$. In those cases where the parallax, and therefore the distance, of the system has been determined, it is found that the mean linear distance of the components from one another is greater than that of the Earth from the Sun. These distances are comparable with the distance of the outermost planets of the solar system from the Sun.

Unlike the other two classes of binaries which are giants or supergiants, visual binaries belong to the main sequence, in other words they are dwarfs. The reason for this becomes apparent when it is remembered that, for their components to be seen individually, they must be relatively near neighbours of the solar system. Their spectral classes range from A to G, but some of them belong to the more advanced classes and therefore have small masses and great densities.

Visual binaries may be grouped, more or less arbitrarily, into the following classes, each of which takes its name from a typical example:

1. **61 Cygni class.** The components do not differ very greatly in magnitude, their mean distances are considerable and they require several centuries for the completion of one revolution around their common centre of gravity.

2. **α Centauri class.** The components, of approximately the same brightness, revolve with a period which can vary from a few years to about a century.

3. **Sirius class.** A brilliant primary accompanied by a very faint companion. The only known members of this class are Sirius and Procyon.

4. **Capella class.** The members of this class are characteristically spectroscopic binaries. Visual measurements of them can be made only with the interferometer. As we have already explained, doubles of this type are important in that the combination of spectroscopic and visual observations gives us a complete knowledge of their elements and characteristics. Stars of this class thus constitute a link between visual and spectroscopic binaries.

Some double stars, having components which are sufficiently wide apart, can even be seen with the naked eye. A well known example is the double Mizar–Alcor in Ursa Major which has a separation of $12'$ and a magnitude difference between the two components of $1^{m}\cdot5$. Another system visible to the naked eye is θ^1 and θ^2 Tauri which has a separation of $6'$ and a magnitude difference of $0^{m}\cdot4$. A severe test of visual acuity is provided by ε Lyrae which has two equally bright components $3'\cdot5$ apart.

The observation of double stars, and the discovery of new ones, has been continued by many generations of astronomers since the classical investigations of the Herschels and of F. W. Struve, whose famous catalogue, *Stellarum duplicium et multiplicium mensurae micrometricae*, was published at Poulkowa in 1837. In 1906 Burnham collected all the observations that had been made up to that year, including his own numerous observations, in his comprehensive *General Catalogue*, which in 1932 was followed by Aitken's *New General Catalogue of Double Stars*. The work of observing and measuring the motion of the components of the 23,000 doubles included in this catalogue represents a formidable task. The motion of the majority of them is very slow, however, and only future observations will enable us to decide which of these systems show an orbital motion from which the elements of their orbit can be determined. Future observations will also show which of these systems have a common proper motion and which are simply optical doubles.

Some of the more interesting examples of each of these classes are described below.

61 Cygni. Bradley in 1755 discovered that this star was double. Its large proper motion suggested that it is a relatively near neighbour of the solar system. It was, in fact, the first star for which the parallax, and therefore the distance, was determined by Bessel, using a heliometer. More recent measurements give its distance as 11·1 light-years, and it is therefore to be numbered among the nearest of the stars. The spectral classes of its two components are K7 and K8, their apparent magnitudes 5·6 and 6·3 respectively, and their absolute magnitudes 8·3 and 8·7. These two stars are therefore dwarfs, of a later type than the Sun, possessing almost identical physical characteristics, and linked together by their mutual attraction, as has been proved by continuous measurements over a long period of years. The early measurements, which were initiated by Struve in 1830, seemed to show that the motion of the secondary component relative

to the primary was rectilinear, at a distance of about 20″, and it was therefore rather doubtful whether this motion was really orbital. More recent observations have, however, proved beyond doubt that the two components are very slowly revolving around their common centre of gravity. Although it is still impossible to calculate the orbit accurately, since only a small arc of the apparent orbit has been observed, yet Zagar recently has been able to use new methods of orbit computation and to derive a good approximation. He showed that the 61 Cygni system has a period of about 700 years, with an eccentricity of 0·4 and a semi-major axis of 24″·4, corresponding to about 80 A.U.

Further investigations of this interesting system have revealed that its total mass is 1·2 times that of the Sun and the individual masses of its components are 0·75 and 0·45 times that of the Sun. These observations have also revealed the existence of perturbations in the motion of the two components, that is small deviations from the perfect orbit, which calculations show must be due to the presence of a third component having a mass 16 times that of Jupiter and which is therefore invisible from the Earth. This is probably a solid body or, in other words, a planet which pursues an eccentric orbit around one of the two components of 61 Cygni having a period of 5 years and being at a mean distance of 2 A.U.

70 Ophiuchi (fig. 10) is another interesting system that has been under observation since 1825. The magnitudes of the two components are 4^{m} and 6^{m}, and their distance from each other varies from a minimum of about 2″ to a maximum of about 7″. The fainter component revolves around the primary with a period of 88 years, so that more than one complete revolution of the system has been observed. The components are, once again, red dwarfs of classes K1 and K6. The primary is about as massive as the Sun, and the companion star only about half as massive. Their distance from the Earth is 16 light-years. As in the case of 61 Cygni, the apparent motion of the fainter component around the primary is subject to small deviations. These, again, can be explained by the presence of a third member of the system, though it is not possible to determine to which of the two main components it is attached. Its revolution, around one or the other, can nevertheless be established as occupying 17 years, at a distance of 7 A.U., and its mass is about 0·01 that of the Sun, or 10 times that of Jupiter. This object must be solid and therefore must be considered as a planet, and even if, like the planets

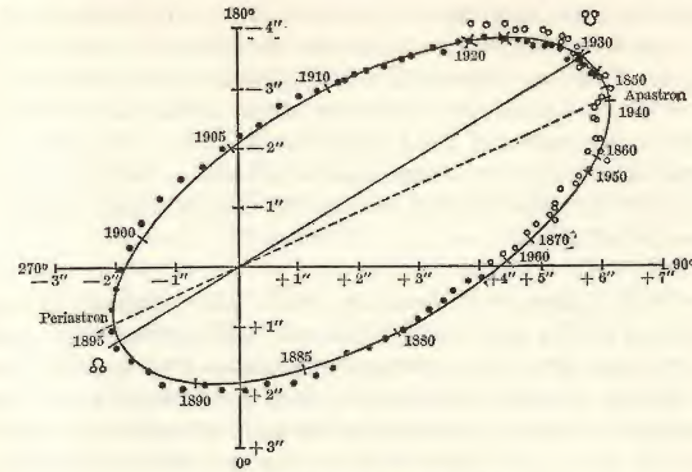


FIG. 10. Orbit of 70 Ophiuchi.

of the solar system, it reflects the light of its two 'suns' it will be invisible to us.

σ **Coronae Borealis.** The distance of this double from the solar system is 68 light-years. The apparent magnitudes of its components are $5^{m}\cdot 8$ and $6^{m}\cdot 7$, their spectral classes F6 and G1 and the corresponding absolute magnitudes are $4^{m}\cdot 2$ and $5^{m}\cdot 1$. The arc of the orbit that has been observed since 1827 is well established, but is still too small a fraction of the whole orbit for its form and period to be determined. The most recent solutions, in fact, indicate periods ranging from 800 to 1,100 years. The masses of the two components are 1·8 and 0·8 times that of the Sun. The observations so far available are insufficient to establish the size of the part of the orbit still unobserved. The determination of the masses, however, can be accepted as accurate because the observations available enable us to determine the curvature of the apparent orbit which is due to the attraction between the two components at a given distance. The brighter component is also a spectroscopic binary and the visual orbit is large. If we accept the longer period quoted above, the mean separation of the two components is about 150 A.U.

α **Centauri** is the double system nearest to the Earth. It is situated in the southern hemisphere, and its components are of classes G4 and K1 and have apparent magnitudes $0^{m}\cdot 3$ and $1^{m}\cdot 7$. As its distance

is 4·3 light-years the absolute magnitude of the components must be $4^m{\cdot}7$ and $6^m{\cdot}1$. Both their magnitudes and masses are of the order of those of the Sun. The period of revolution is 80 years, the eccentricity of the orbit is 0·5, the inclination of the orbital plane is 79° and the mean separation of the components is 23 A.U. Because of its nearness to us, its proper motion is considerable and when it is combined with its radial velocity, it is found that its spatial velocity is about 19 miles/sec.

ξ Ursae Majoris. An interesting double since each of its components is itself a spectroscopic binary. Their apparent magnitudes are $4^m{\cdot}4$ and $4^m{\cdot}9$, their absolute magnitudes $5^m{\cdot}2$ and $5^m{\cdot}7$ and they belong to classes F9 and G2. Their period is 60 years, their masses are 1·3 and 1·0 times that of the Sun, and their mean separation is 21 A.U. This double was discovered and observed by Struve in 1826. Wright, in 1900, discovered that the brighter component is a spectroscopic binary. Later the accurate investigation of the visual orbit revealed a perturbation in the motion of the double with a period of 1·8 years, which corresponded with the period of the radial velocity variation and hence was ascribed to a spectroscopic companion of the primary. Later it was discovered that the fainter companion is also a spectroscopic binary, with a period of about 10 days. The system is therefore quadruple.

Krüger 60. This system has two components which are of low luminosity, but it has a large proper motion and a large parallax. It is to be numbered among the least luminous stars known, being visible to us only on account of its relative nearness to the solar system. The apparent magnitudes of the components are $9^m{\cdot}7$ and $11^m{\cdot}3$, their period is 44 years, and they belong to classes M4 and M6. As their distance is 12·7 light-years, their absolute magnitude must be $11^m{\cdot}8$ and $13^m{\cdot}3$, and hence their luminosities are only 0·002 and 0·0005 that of the Sun respectively. They lie at the extreme end of the main sequence, their masses, which are among the smallest known, are 0·27 and 0·18 that of the Sun. Their mean separation is 9·6 A.U.

The spectrum of the fainter component contains emission lines, notably the H and K lines of ionized calcium. This is an indication of the instability of the star. Indeed during 1951, this star increased noticeably in brightness, reaching magnitude $9^m{\cdot}9$ and rivalling its normally brighter companion. After only a few minutes it relapsed

to its normal brightness. This outburst must have been a 'chromospheric eruption' or flare, such as is observed on a much smaller scale on the Sun, and as has been observed on other stars of the same type.

Sirius. In 1834 Bessel announced that the proper motion of Sirius, the brightest star in the sky, is variable. Some years later he established the same phenomenon in the case of Procyon, and was able to show that in each case this was caused by the attraction of an invisible companion star. 'I am convinced,' as he wrote to Humboldt, 'that Procyon and Sirius are true binary systems, each consisting of one visible and one invisible component. We have no reason to believe that luminosity is a necessary quality of cosmic bodies. The visibility of countless stars is no argument against the invisibility of just as many others.'

Later the orbit of this invisible companion was determined, as well as its mass relative to that of Sirius. In 1862 Clark succeeded in finding visually this faint object at a distance of about 10″ from Sirius and close to its predicted position. Since that time it has completed one full revolution, and the elements of its orbit, which are now known very accurately, are in good agreement with those derived theoretically from the perturbations of the motion of Sirius. The apparent magnitudes of this pair are $-1^m{\cdot}6$ and $8^m{\cdot}4$. Because of the great brightness of Sirius a powerful telescope is needed to show its companion; even then it is invisible when it is at a minimum distance, slightly less than 2″, from its primary. The period is 50 years and the eccentricity of the orbit is 0·60. The mean separation of the two components is 20·4 A.U., and their distance from the Earth is 8·6 light-years. Their absolute magnitudes are $1^m{\cdot}3$ and $11^m{\cdot}3$, they belong to spectral classes A0 and F0, and their masses are 2·44 and 0·96 times that of the Sun, respectively. Sirius is thus 30 times as luminous as the Sun, and 10,000 times as luminous as its companion. As we have already said, this companion is a 'white dwarf' with a density about 60,000 times that of water, whereas the density of Sirius is 0·4. The spectrum of this unusual companion star, which is of a type rather more advanced than that of Sirius itself, also has unusual characteristics, such as enhanced lines of low intensity. The same feature has been found in the spectra of other white dwarfs.

The system of Sirius has been suspected of being not double, but triple, and some observers have succeeded in detecting the third component close to the second. Zagar and others, employing methods

designed to confirm the law of areas in the case of binary orbits, have shown that the velocity-curve of the fainter companion is subject to an oscillation which can be explained by the presence of a third member of the Sirius system, revolving around the second in a period of 6·3 years in an orbit having a semi-major axis of 1″·3. The mass of this third component has been calculated as being 0·05 that of the second, and hence it does not materially reduce the very high figure derived for the density of the latter.

SPECTROSCOPIC BINARIES

ξ Ursae Majoris is typical of about 5% of the total number of visual binaries known, which are in reality triple or multiple systems. Often a close pair is accompanied by one or more relatively distant companions which have the same proper motion as the pair. Besides such proper motion, an actual orbital motion may exist but because of the great distance this will necessarily be of very long period and will be observed only after an extended series of observations. Castor (α Geminorum), for example, is a visual binary having a period not yet accurately determined, which is certainly longer than 300 years. The two components are both of class A0 and have apparent magnitudes $2^{m}\cdot0$ and $2^{m}\cdot8$, absolute magnitudes $1^{m}\cdot4$ and $2^{m}\cdot2$, a mean separation of 80 A.U. and a combined mass of 5·5 times that of the Sun. Accompanying this pair is a faint companion star of apparent magnitude $9^{m}\cdot5$ at a distance of 7″·3, which appears to have the same proper motion and is probably revolving around the pair in a period greater than 10,000 years. Later it was discovered that all three components are spectroscopic binaries having short periods so that Castor is in fact a system consisting of six stars.

ε Lyrae (p. 115) is another multiple system. It consists of two pairs having individual separations of 2″·5 and 3″·5. They have a common proper motion and the distance between them is 207″. The period of the close pair must be many centuries, and that of the wider pair many hundreds of thousands of years. The brightest of these four stars, which has an apparent magnitude of $4^{m}\cdot6$, is a spectroscopic binary.

In 1650 Riccioli discovered the first double star: ζ Ursae Majoris (Mizar). This was also the first star to be photographed at Harvard Observatory in 1857, and later Pickering, at the same

observatory, discovered that the primary component of the visual system is a spectroscopic binary. His discovery was the result of noticing that on some plates the spectral lines of the spectrum of this component were single, while on others they were double, and that the phenomenon was repetitive in a period of 655 days. The doubling of the spectral lines may be explained if we assume that the star is a binary, with components too close together to be separated visually, and that they are of approximately the same brightness, so that their two spectra are seen superimposed one on the other. If they are revolving with a given velocity around their common centre of gravity in an orbit whose plane is almost parallel to the line of sight, then their velocity projected on the plane at right angles to the line of sight will vary periodically between maximum and minimum values.

According to the Doppler effect, the lines of the spectrum of each component will be displaced from their mean position by an amount which is proportional to their linear velocities. We shall have shift towards the violet when one component, in its rotation around the centre of gravity of the system, is approaching the Earth and a shift towards the red when it is receding. Since one component is approaching the Earth while the other is receding from it, it follows that the lines will be displaced in opposite directions, and will therefore appear double in the spectrograms. Twice in the course of each revolution, the orbital motion of the two components will be at right angles to the line of sight, and if the two spectra are alike, their lines will at these times coincide, and no doubling will be observed.

If, on the other hand, the lines are single but are always displaced towards the red or the violet, relative to their normal wavelengths, given by the comparison spectrum of a suitable terrestrial source, the system, as a whole, is said to have a radial velocity either of recession or of approach relative to the Earth. This radial velocity is a very important datum because, as we shall see later, when it is combined with the proper motion of the system, it gives the true motion of the star through space. The explanation of the doubling of the lines in the spectrum of Mizar has subsequently been confirmed by the spectra of many other stars, so that Mizar was not only the first visual binary to be discovered, but also the first spectroscopic binary.

The two spectra of a spectroscopic binary will be seen superimposed when the components are approximately of the same magnitude. When, however, one component is more than about two

magnitudes brighter than the other, the spectrum of the fainter will be invisible and the periodic displacement of the lines will not be revealed by their doubling though it will be possible to measure it with the aid of a comparison spectrum. If the plane of the orbit of the system is parallel or nearly parallel to the line of sight, the components will eclipse one another. In such a system, known as an 'eclipsing binary', it will be possible to observe the spectrum of the fainter component. If, as is more commonly the case, the inclination of the orbital plane is such that eclipses cannot occur, the variable radial velocity of the brighter component will be the only indication of the existence of the binary system.

About 1,500 of the 7,000 stars that have been examined have been found to have variable radial velocities. Sufficient observations of about 400 of these have been obtained for the elements of their orbits to be calculated. In approximately one sixth of these the superimposed spectra of both components can be seen, and a few of them have also been observed as visual binaries.

Since the spectrographic observations of these systems are normally undertaken with spectrographs of low dispersion, it will be realized that only those systems which have wide variations of velocity can be detected. In other words, those systems which are relatively massive are the most easily observed, and especially those with short periods of a few days or even a fraction of a day.

The problem of determining the orbit of a spectroscopic binary from measurements of the radial velocity corrected for the motion of the observer is very different from that of calculating the orbit of a visual binary from the measurements, obtained with a micrometer, of the position angle and of the distance. We have seen that these enable us to plot the orbit of the companion star around the primary although its linear dimensions are unknown. Radial velocities, on the other hand, when plotted against time, produce a periodic curve which in the special case of a circular orbit is a sine curve. In the more general case of elliptical orbits the sine curve will be more or less distorted (fig. 11). The elements of the true orbit of the component, whose spectrum is visible, can be derived from this curve, or if both spectra are observable, both orbits may be derived.

Whereas in the case of visual binaries the period is expressed in years and the semi-major axis is given in seconds of arc, in the case of the spectroscopic binary the same quantities are expressed in days and in miles. Once the radial velocity curve which best fits the observations has been plotted, it is simple to distinguish between its

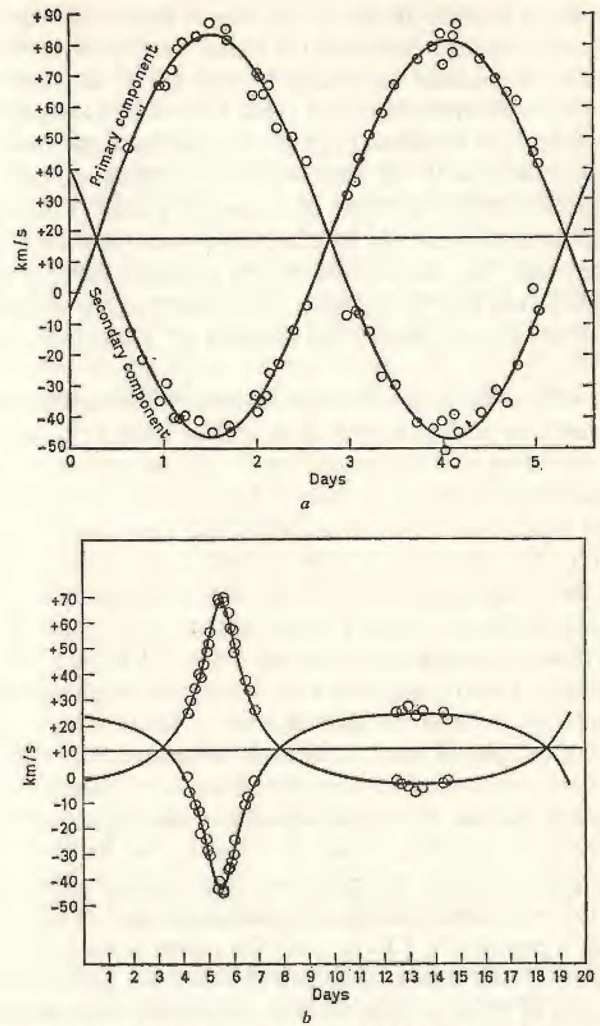


FIG. 11. Velocity curves. (a) ν_4 Eridani (b) χ Arietis

periodic and its systematic component which is due to the constant radial velocity of the system. The elements of the orbit, with the exception of two which are indeterminable by the very nature of the observations, can then be derived by a variety of graphical and analytical methods or by a combination of both. Of the two elements that cannot be determined in this way, one is the position angle of the nodes, that is of the line of intersection of the plane of the orbit

and the plane at right angles to the line of sight, and the other is the inclination of the orbit, since the radial velocity depends only on changes in the distance separating the star from the observer, and these may be exactly the same for orbits of various sizes and inclinations. All that can be determined is the quantity $a \sin i$, where a is the semi-major axis of the orbit, and i its inclination, but not the actual distance of the star from the centre of gravity. This quantity, expressed in miles, can only be discovered when, as occurs in a few cases, the system can also be observed as a visual binary. In this case it is possible, not only to complete the determination of the orbital elements, but also to derive the distance of the system from the Earth.

About 60% of those spectroscopic binaries whose orbits have been determined have periods shorter than 10 days while 30% have longer periods extending to 100 days and more. The shortest known period for a spectroscopic binary is that of 8 hours of W Ursae Majoris, while the longest are those of ε Hydrae (15 years) and VV Cephei (20 years). The shortest possible periods are probably those of binaries the components of which are almost in contact, while the longest are similar to those of visual systems and constitute a link between these two categories of binary stars. It has been found that a relationship, which is important for its physical implications, exists between the period and the spectral class of spectroscopic binaries. Those of short period most commonly belong to the early classes from O to G, while those of long period are more numerous among the classes K and M. The radial velocity of the brighter component ranges from 3 miles/sec., which is close to the limit of possible measurement, to about 300 miles/sec. The highest relative orbital velocity yet encountered is 342 miles/sec. and is that of the V Puppis which has a period of 1·5 days. Both the components of this system are of class B1 and their spectra can be observed. The eccentricities of the orbits of spectroscopic binaries are considerably smaller than those of visual binaries. They are of the order of 0·2 and increase with the period.

The spectroscopic binaries can be classified on the basis of these data and of these characteristics, just as the visual binaries were classified. A few of the best known and most interesting are described below.

Capella (α Aurigae). This is both a visual and a spectroscopic system. It was discovered as a spectroscopic binary by Campbell at

Lick Observatory in 1890. The spectra of both components can be seen to be superimposed, and by means of the periodic Doppler displacements of their absorption lines the orbit of the system can be derived. Its period is 104 days. From the elements of the orbit it follows that the separation of the two components is about 0″·05, which is within the reach of Michelson's interferometer used in conjunction with the Mt. Wilson 100-inch reflector. Measurements made with this instrument at different times have in fact confirmed this angular separation and enabled the calculation of the elements of the visual double to be made. The two components have apparent magnitudes of $0^{m}{\cdot}8$ and $1^{m}{\cdot}1$ and they belong to classes G5 and F6. The radial velocity of the primary varies from −2·5 to +35 miles/sec., and that of the companion star from +39 to −2 miles/sec. (fig. 12).

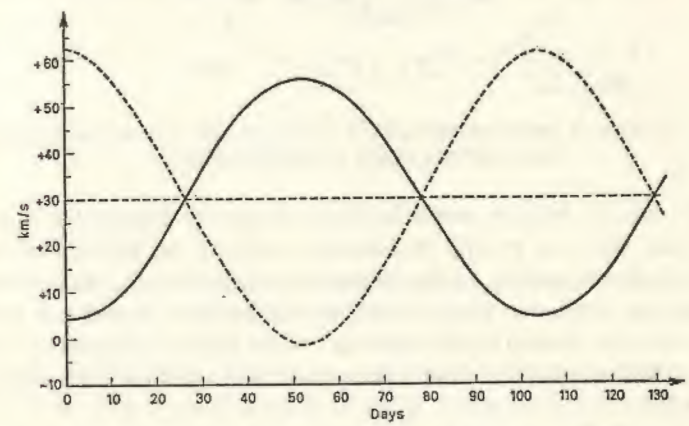


FIG. 12. Velocity curve for Capella. The dashed curve represents the radial velocity of the secondary component.

From the ratio of the amplitudes of these variations it can be calculated that the ratio of the masses of the two components is 1·26. The orbit may be regarded as circular, with a diameter of 79 million miles. The derived masses of the two stars are then 4·2 and 3·3 times that of the Sun, and their absolute magnitudes $-0^{m}{\cdot}3$ and $0^{m}{\cdot}2$. Their radii are 10 and 8 times that of the Sun, and the corresponding densities 0·006 and 0·009 g/cm³. They are therefore yellow giants.

From a study of the superimposed spectra of the two components of the system when it is in various positions of the orbit (fig. 13), O. Struve concludes that the spectrum of the primary can easily be identified as belonging to class G5, while the lines of the spectrum

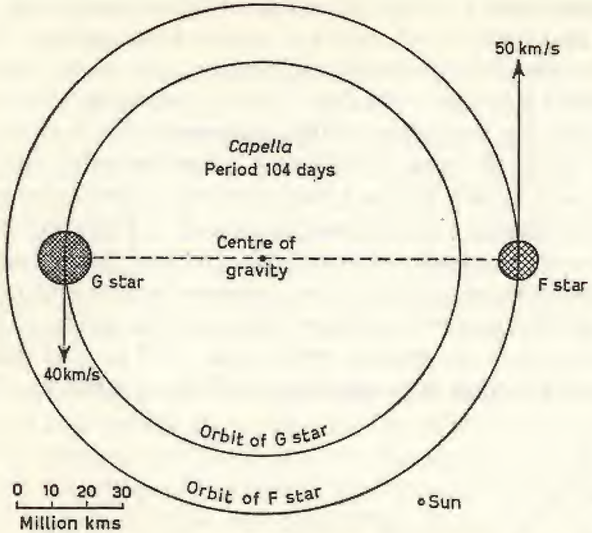


FIG. 13. Orbits of the two components of Capella around their centre of gravity. The orbits are almost circular. (O. Struve.)

of the fainter, F6 star, are difficult to recognize. This is due to the fact that they are greatly broadened, probably on account of the rapid turbulent motion of the atmosphere of the F6 star. The distance separating these two stars is such that anomalies should not exist but some are present in the spectrum of the fainter companion, and Struve believes that this fainter companion of Capella is not a normal giant.

Castor (α Geminorum) (fig. 14). We have already described the visual system of Castor. Both components are spectroscopic binaries and present an interesting contrast in the shape of their orbits, particularly since they are of the same spectral class. The primary and its invisible companion form a spectroscopic binary having a period of 9·2 days and an eccentricity of 0·5. The half-amplitude of the radial velocity curve is K = 8 miles/sec. and $a \sin i$ = 870,000 miles. The fainter component also is a spectroscopic binary. Its period is 2·9 days, its eccentricity is 0·01, K = 19·8 miles/sec. and $a \sin i$ = 808,000 miles. As regards the masses of these two pairs, only the mass functions can be derived, and these show that the ratio of the masses of the various components are very different in each system.

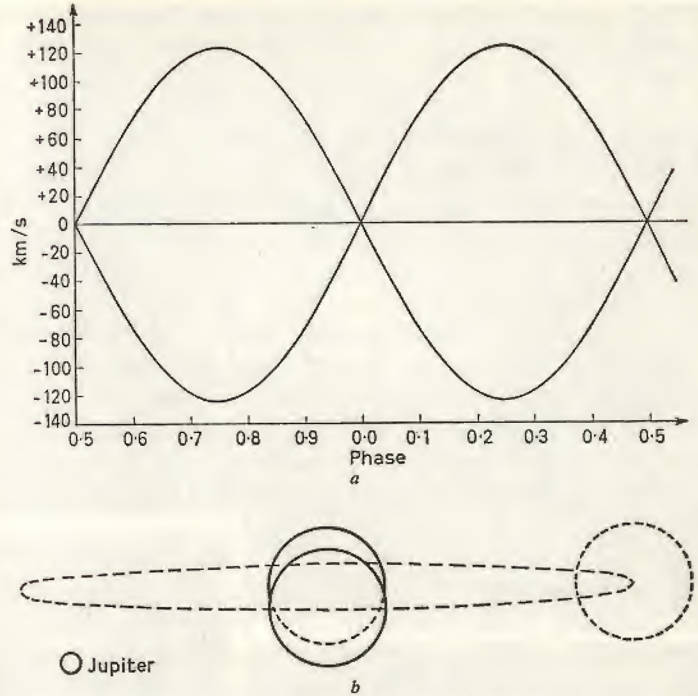


FIG. 14. Castor (α Geminorum) (a) velocity curve (b) diagram of the system. (O. Struve and G. E. Kron.)

Spica (α Virginis). This system, detected by Vogel in 1890, was one of the first spectroscopic binaries to be discovered. Its apparent magnitude is $1^{m}{\cdot}2$ and it belongs to the spectral class B2. The spectra of both components are visible, and from the radial velocity curve it can be deduced that the period is 4·0 days and the eccentricity 0·1. The half-amplitude of the radial velocity curve of the primary and of the companion referred to the centre of gravity of the system, shows that $K_1 = 78{\cdot}3$ miles/sec., and $K_2 = 125{\cdot}5$ miles/sec. The semi-major axes of the two orbits, relative to the centre of gravity of the system, are respectively $a_1 \sin i{=}4$ million miles and $a_2 \sin i{=}6{\cdot}8$ million miles. It was later discovered by Stebbins that the apparent brightness of this system is variable, and that it belongs to the class of eclipsing variables. At the present time we can give only the minimum values for the masses of the two components, until such time when by means of other data it will be possible to obtain the inclination of the orbit. The masses are found to be $\mathfrak{M}_1 \sin^3 i = 9{\cdot}0$

and $\mathfrak{M}_2 \sin^3 i = 5{\cdot}6$ times the mass of the Sun. The parallax which has been obtained only approximately also implies that these are giants.

β **Aurigae.** The spectra of both components of this star, which has an apparent magnitude of $2^m{\cdot}1$, are observable. They are of equal intensity, and both are of class A0. β Aurigae has been very extensively observed since it belongs also to the class of eclipsing variables. The period is 3·96 days, the orbit is circular and the data determined for this system are: $K_1 = 67{\cdot}7$ miles/sec., $K_2 = 69$ miles/sec., $a_1 \sin i = 3{\cdot}6$ million miles, $a_2 \sin i = 3{\cdot}7$ million miles, $\mathfrak{M}_1 \sin^3 i = 2{\cdot}2$ and $\mathfrak{M}_2 \sin^3 i = 2{\cdot}2$ times the mass of the Sun. Since the inclination of the orbital plane is 77°, the masses of both components must be 2·4 times that of the Sun. It seems that the period, like that of several other spectroscopic binaries, is slowly increasing and this may be an important factor in the evolution of the system.

ξ **Ursae Majoris.** We have already described this quadruple system when discussing visual binaries (p. 118). The spectroscopic binary consisting of the brighter star of the visual pair (*A*) and its spectroscopic companion (*a*) has a period of 669 days, its eccentricity is 0·5, $K = 5$ miles/sec., and $a \sin i = 38{\cdot}5$ million miles. The other spectroscopic system has a period of 4 days, the orbit is circular, $K = 2{\cdot}5$ miles/sec., and $a \sin i = 171{\cdot}497$ miles. The inclination of the *Aa* system is found to be about 90°, so that this system may well be also an eclipsing binary although this in fact has not yet been confirmed. The inclination of the other system (*Bb*) is small. The density of these components has been calculated as being approximately 1·2 that of the Sun.

ECLIPSING BINARIES

Stars are said to be 'variable' when, as we shall describe in greater detail later, they do not emit a steady and constant flux of light, as do the majority of the stars, but are subject to regular and irregular periodic variations of brightness.

This brightness variation may be due to one of several causes. The one which interests us at the moment is the mutual eclipse of two or more bodies as they revolve around their common centre of

Plate 8. Stellar Populations I and II. (*left*) Andromeda Nebula, photographed in blue light, shows giant and supergiant stars of Population I in the spiral arms. The hazy patch at the upper left is composed of the unresolved Population II stars. (*right*) NGC 205, companion of the Andromeda Nebula, photographed in yellow light shows stars of Population II. The brightest stars are red and 100 fainter than the blue stars of Population I

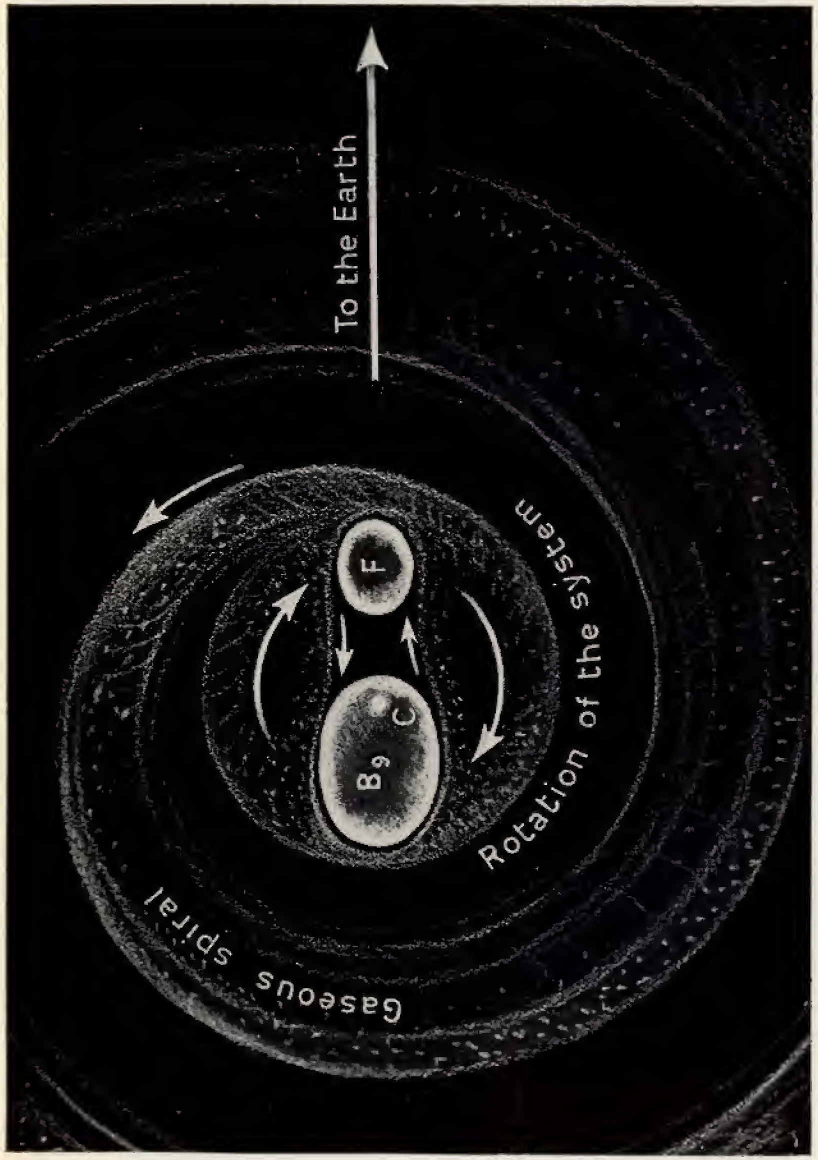


Plate 9. The β Lyrae system according to Struve and Kuiper. B_9, main component: F, secondary component: C, centre of gravity of the system

gravity. A system of this sort is known as an 'eclipsing binary', and these stars form a very important class among double and multiple stars. The well known second magnitude star β Persei (Algol) was discovered to be a variable by Montanari in 1668, but it was not until more than a century later that the periodicity of its variation was detected, and the suggestion was put forward that its variation of brightness might be due to the mutual eclipses of the two components. Another century later, as a result of the study of its spectrum, Vogel finally proved that the star was in fact a double star.

In order that we on the Earth should be able to observe the phenomenon of the mutual eclipse of the two components of a binary star, the inclination of its orbit must be close to 90°. In such a case, when one component passes in front of the other, the total light of the system will be reduced, and this reduction will depend on the physical characteristics of the system in question. To be more precise it will depend on the ratio of the radii of the two components, their relative intensities per unit area of the surface, the size of the area that is eclipsed, the ellipticity and any limb-darkening of the components similar to that observed on the Sun. It will also depend on the inclination and eccentricity of the orbit, the effect of tides, the reflectivity and libration of the components, the possible presence of a third body, and the probability that one or both components are of intrinsically variable brightness. Thus the observed light-curve is a function of at least eleven different factors. It is recognized, however, that some of these have a negligible effect and that the fundamental factors are the first three.

The light-curves of these binaries have therefore various forms, and from them we may deduce, with certain restrictions, the orbit and other characteristics of the system. If the inclination of the orbit is much less than 90° the eclipses will be partial. The total light received from the system will fall to a minimum when the two components lie on the same line of sight, and after that it will gradually increase again. If the orbit is seen almost edge-on, one of the eclipses will be total and the other annular. If the two components are very different in size, the apparent brightness of the system will decrease during total eclipse, when the smaller component is hidden by the larger, and again during the subsequent annular eclipse. If the orbit is circular, the area of the star which is eclipsed will be the same at the time of the two minima and the principal minimum will therefore occur when the star with the greater surface brightness is eclipsed. The maximum observed amplitude of the light-curves is of about

4 magnitudes, but the most common amplitude at the principal minimum is about 1·5 magnitudes.

It is not possible to make a hard and fast classification of eclipsing binaries in well defined categories but it is usual to divide them into classes each of which takes the name of a bright and well-known star which is more or less typical of the class as a whole, such as Algol and β Lyrae.

Algol is the type star of those eclipsing binaries which for the greater part of the time maintain a steady brightness due mainly to the primary. When the fainter star passes in front of it there will be a temporary reduction of the brightness, the duration and other characteristics of which will depend upon the circumstances of the eclipse, after which the system will regain its original brightness. This phenomenon will be repeated regularly and periodically (fig. 15, p. 134). When the fainter component is eclipsed there will again be a reduction of the total brightness of the system, but this time the minimum will be smaller than before. This can be seen in the light-curve of Algol, but since the fainter star makes only a negligible contribution to the brightness of the system as a whole, the secondary minimum is barely perceptible, and its existence was only proved fairly recently by means of sensitive photoelectric measurements. The form of the light-curve of Algol also proves that both components must be ellipsoidal in shape.

β Lyrae is the type star of the second class of eclipsing binaries the brightness of which varies continuously between the two minima. The size of the components is large compared with that of the orbit, so that in the course of their revolution around the centre of gravity of the system they cover one another almost continuously and therefore the partial or total eclipses last for the whole period. If in addition to this the components are ellipsoidal in form and exhibit limb-darkening, it is clear that the system will never be able to emit a steady flux of light. The two minima of the light-curve are usually unequal, depending on the difference of brightness of the two components.

In a sub-class of systems of this type, named after the star W Ursae Majoris, are included systems which have two minima of the light-curve which are equal, so that in each period there are two similar and regular light variations. In reality this distinction is made more as a matter of convenience in nomenclature than because of the existence of inherent differences. This has been realized particularly since the discovery of the secondary minimum of Algol.

The periods of eclipsing binaries, like those of spectroscopic binaries, are short compared with the periods of visual pairs. A few have longer periods than 10 days, but the majority have shorter periods than this, of the order of about 3 days. Binaries belonging to the W Ursae Majoris class may have periods even shorter than 1 day. Altogether, more than 2,000 eclipsing binaries have so far been discovered, 70% of which belong to the Algol type, 15% to the β Lyrae type, 10% to the W Ursae Majoris type and the remainder belong to a class which has various phases of brightness variations which are irregular, perhaps as a result of the presence of other bodies in the system.

Russell showed, in 1912, that once the period and light-curve of a system had been determined with the greatest attainable accuracy, the characteristic of the light-curve could be used to deduce the orbital elements of the system, subject to certain limitations. In the general case the number of unknowns is at least thirteen, so that the problem is a difficult one. The orbit may be circular or elliptical, and the components of equal or unequal size and brightness. The hemispheres facing the observer may be uniformly bright or affected by limb-darkening owing to the presence of an atmosphere surrounding them. They may be spherical or of some other shape, in fact the components may be ellipsoidal, and furthermore, in view of their mutual proximity and hence strong reciprocal attraction, they may be distorted to a considerable extent by tides. The hemispheres facing one another may be brighter than the other two by an amount that will depend on the intensity of the radiation emitted by the two stars. According to Russell, the thirteen unknowns may be listed as follows:

Elements of the orbit	*Elements of the eclipse*
a semi-major axis	r_1 radius of primary component
e eccentricity	r_2 radius of fainter component
ω longitude of periastron	L_1 luminosity of primary component
i inclination	L_2 Luminosity of fainter component
P period	At least three constants, defining the size of the elongation, the limb-darkening and the increase of intensity of one component as a result of the radiation of the other.
t_0 epoch of the principal conjunction	

Owing to the closeness of the components to one another they cannot be individually distinguished, and therefore it is impossible to determine the longitude of the nodes. If the system is also measured as a spectroscopic binary, and if it is assumed that i is known since

it must always be near to 90°, a can be obtained in absolute units. Whereas the spectroscopic observations give the variable radial velocities of one or both components around their centre of gravity, photometric measurements take as the unit of measurement the semi-major axis of the relative orbit of the system. If we write a_1 and a_2 for the two semi-major axes expressed in miles as derived from spectroscopic measurements, and a for that derived from photometric measurements, we have that $a = a_1+a_2$. Hence if both components can be observed spectroscopically, the value of a, expressed in miles, can be derived, and, as a consequence, also the linear values of r_1 and r_2, while photometric measurements can only give the ratios r_1/a and r_2/a. The absolute values of L_1 and L_2 can only be obtained if we know the parallax of the system. Taking L_1+L_2 as unity, the luminosity of the two components can be expressed in terms of this unit. The period usually can be accurately determined, and so can the time of the primary minimum of the light-curve. The constants relating to the ellipticity and to the effect of reflection can be derived from the brightness between eclipses, but these are usually unimportant effects which, like the limb-darkening, can be neglected in a first approximation. Thus there remain six unknowns.

In these short-period systems the orbits must be circular or nearly so, as is confirmed by spectroscopic observations and by the position of the secondary minimum, so that for the purpose of calculations, the eccentricity may be taken as zero. The problem is then considerably simplified, and may now be stated in the following form: given two spherical stars with uniformly bright discs, which are revolving around their common centre of gravity in circular orbits and eclipsing one another as they revolve, to determine from the observed light-curve, their relative sizes, their luminosity and the inclination of the orbit.

The problem was solved by Russell for this simplest case, and subsequently by Shapley and Russell for the more general case in which account was taken of limb-darkening. Numerous tables were also calculated to assist in the determination of these orbits.

A statistical investigation of these systems, which exhibit an interesting variety and of which new examples are being continuously discovered by photometric and spectroscopic observations, has recently been undertaken by Fracastoro. He concluded that the fundamental parameter is the period P, which is related to the other physical characteristics of the systems, and in particular to their absolute luminosity. This correlation between period and luminosity

has been confirmed in the case of systems consisting of two ellipsoidal components which include those belonging to the β Lyrae and W Ursae Majoris type. Systems which have periods ranging from 0·2 to 1 day are associated with a mean spectral class between K and F. Their absolute magnitude ranges from +7 to +2, and the mass increases gradually from 1 to 2 or 3 times that of the Sun, while the density decreases from about 3 to 0·2 that of the Sun, and the semi-major axis of the orbit varies from 600,000 miles to 2·5 million miles. As the period increases, from one to about ten days, the spectral class changes to B and A, the absolute magnitude ranges from −3 to −4, the mass from 10 to 20 times that of the Sun, the density from a hundredth to a thousandth that of the Sun, and the semi-major axes of the orbit increase with the period from 3 to 25 million miles and even more. All these systems, whether giants or dwarfs, thus belong to population I.

The principal characteristics of a few of these eclipsing binaries are summarized below.

Algol (β *Persei*) (fig. 15). We have already referred to the light-curve of this complex system. The long series of minima that have been observed since the discovery of this eclipsing binary indicate that it is accompanied by two other stars, so that in reality we ought to think in terms of a quadruple system. The brighter of the two components of the eclipsing binary is a type B8 star, and the fainter belongs to class F8. At the principal minimum the primary is partially eclipsed by the fainter companion with a loss of 1·2 magnitudes, while when the fainter star is eclipsed by the primary we have a secondary minimum with a loss of only 0·05 magnitudes. The loss of brightness at the secondary minimum is almost exactly equal to the gain obtained from the reflection effect, confirming that the companion does not contribute effectively to the brightness of the system. From the light-curve it can be seen that the period is 2·87 days, and that the inclination of the almost circular orbit is 82°. The radius of the fainter component is slightly larger than that of the primary, they are 3·7 and 3·2 times respectively that of the Sun. The mass of the primary is 5 ⊙ and its density 0·16 ⊙ while the corresponding values for the companion are 1 ⊙ and 0·01 ⊙. The distance separating the centres of the two stars is about 6 million miles. It appears that both these components are rotating on their axes, that they are slightly ellipsoidal, and that they exhibit limb-darkening, indicating that they are enveloped in extensive atmospheres.

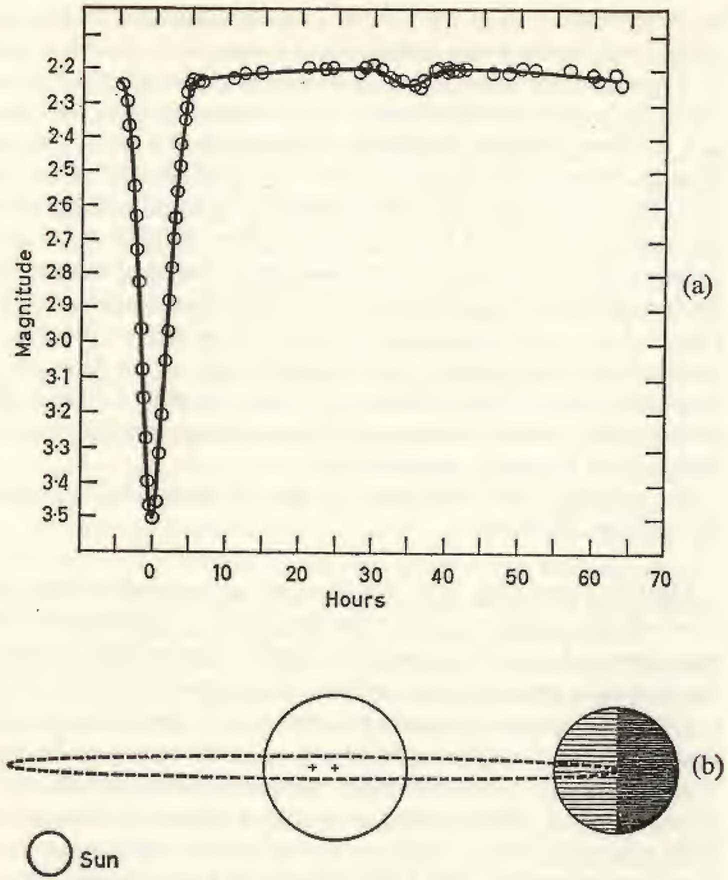


FIG. 15. Algol (β Persei) (a) light-curve (b) diagram of the system.

The revolution periods of the third and fourth members of the system are respectively 1·87 and 188 years. The total mass of the four components is 11 times that of the Sun. The absolute magnitudes of the two components of the binary system are respectively −0·2 and +2·5 and they are thus giants of population I.

β **Lyrae** (fig. 16). This is another eclipsing binary of very complex structure, particularly as regards the characteristics and variation of its spectrum, which have been the subject of a great number of investigations. The light-curve reveals a period of 12·92 days, with an amplitude of 0·81 magnitudes at the principal minimum and 0·43

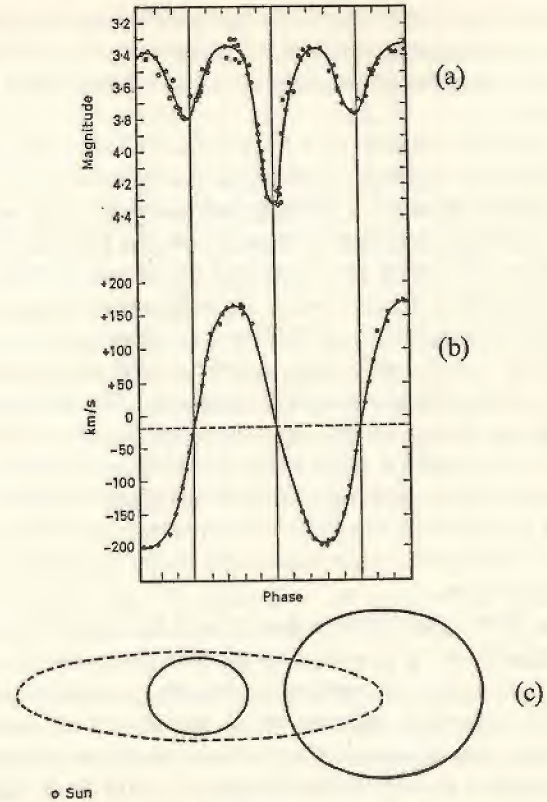


FIG. 16. β Lyrae. (a) light-curve (b) velocity curve (c) diagram of the system.

at the secondary. The primary thus contributes 0·63 of the total light of the system, and its radius is 0·26 of the distance separating the centres of the two components. The ratio between the radius of the primary and that of the companion is 0·42 and the inclination of the orbit is 74°. After having been observed and studied by a great number of investigators since the time of its discovery in 1784, the mystery of its structure began to be unravelled when spectroscopic observations were introduced, and it became possible to consider β Lyrae as a spectroscopic binary as well as an eclipsing binary. Since the amount of light emitted by the system varies continuously between the two minima, it must be assumed that the components are ellipsoidal, with different surface brightness, and that they are revolving around their common centre of gravity in an extremely narrow orbit. Matters have been further complicated both by the difficulty

of interpreting its spectrum and by the fact that very precise photometric measurements made with a photoelectric cell, have revealed irregular variations in the light-curve of β Lyrae from one cycle to the next.

Its spectrum consists of a normal part which can be assigned to class B9, upon which is superimposed a type B5 spectrum which is more violet and hence slightly hotter, but which has characteristics that are difficult to interpret. It was from the Doppler displacements of the lines of the B9 spectrum that the elements of the orbit were deduced, treating the system as a spectroscopic binary. It was confirmed that the period is 12·92 days, that the orbit is almost circular, and that $K = 114{\cdot}3$ miles/sec., $a_1 \sin i = 20{\cdot}2$ million miles and that $i = 80°$ using the photometric elements. The individual masses, deduced by other means, are $\mathfrak{M}_1 = 65 \odot$, $\mathfrak{M}_2 = 84 \odot$ so that $a_1 + a_2 = 48{\cdot}3$ million miles (Plate 8). However, the lines of the B5 spectrum do not show any periodic variation but have a constant velocity of approach towards the solar system amounting to approximately 31 miles/sec., while that of the centre of gravity of the system is 11·8 miles/sec.

From these results Struve has argued that the B5 spectrum does not originate in the reversing layer, that is the outermost layers of the stars forming the system as happens on the Sun, but in an extremely extensive gaseous cloud enveloping the whole system. Developing his theory further, on the basis of the spectroscopic characteristics and on the displacements of the lines, Struve showed that the larger, B9 component emits 96% of the total light of the system. It is a giant star (Plate 9) many times larger than the Sun, while the companion, which is too faint for any trace of its spectrum to be detected, must have a lower temperature corresponding to class F. The radius of the principal star is about twice that of the F component. A jet of gas is emitted, rather in the form of a gigantic solar prominence, from the B9 star in the direction of the smaller component of class F, on the side which becomes visible to us after the occurrence of the eclipse. The gas is emitted with a velocity of approximately 186 miles/sec., and the F component hides it from us during the course of its revolution until it suddenly becomes visible in absorption. When the jet passes over the F star and envelops it, the conservation of angular momentum will cause a part of it to be deflected, with the formation of a condensation at a mean distance from the surface of the B9 star equal to about twice its radius. This condensation is continuously fed by the jet of gas, and will develop

into the ring of matter enveloping the system. The total width of the emission lines is of the order of 10 Å which is equivalent to about 426 miles/sec. Since the velocity is greater than that due to expansion, the nebulous ring must itself have a velocity of rotation exceeding 186 miles/sec.

To sum up, this unusual system must be regarded as consisting of two components which are surrounded by a common envelope, and which can therefore be termed a binary system in contact. Theoretical astrophysics shows that if the components of such a system are, like those of β Lyrae type, unequal, the system will be unstable. As long as this inequality persists streams of matter will flow from the primary towards the fainter component. The system of gaseous streams thus produced can explain the observed complexities in the spectrum and the various characteristics of the fluctuation of light. The transfer of matter from the primary to the fainter component and the gaseous envelope will have the effect of shortening the period.

W Ursae Majoris (fig. 17). This star, the type-star of a sub-class to which reference has already been made, has one of the shortest periods known, namely 0·334 of a day. It is a G0 dwarf with a magnitude at maximum of +7·9. Its light-curve shows two equal minima having an amplitude of $0^{m}{\cdot}60$. We must therefore have partial eclipses of two ellipsoidal stars of the same size which emit the same quantity of light and their radius is equal to 0·78 times that of the Sun. Their respective masses are $0{\cdot}69 \odot$ and $0{\cdot}49 \odot$, their densities $2{\cdot}1 \odot$ and $1{\cdot}5 \odot$ and $a_1 + a_2 = 951{,}000$ miles.

UW Canis Majoris. This star of 4·5 magnitude was discovered to be a spectroscopic binary more than thirty years ago. At first, only the O9 spectrum of the primary was observed, but more recently it has been possible to distinguish that of the fainter component which is of the same type. In 1936 it was further discovered that the system is also an eclipsing binary with a light-curve which has two well-defined and almost equal minima of amplitudes $0^{m}{\cdot}33$ and $0^{m}{\cdot}32$. The spectroscopic and photometric data show that the period is 4·4 days, the inclination of the orbital plane is 68°, and the semi-major axis is 23 million miles. The radii of the two components are $r_1 = 23 \odot$ and $r_2 = 17 \odot$, their masses $\mathfrak{M}_1 = 40 \odot$ and $\mathfrak{M}_2 = 31 \odot$, their densities $\rho_1 = 0{\cdot}003$ and $\rho_2 = 0{\cdot}006$ that of the Sun and the absolute magnitude is $-6{\cdot}7$. This system, and the similar one of

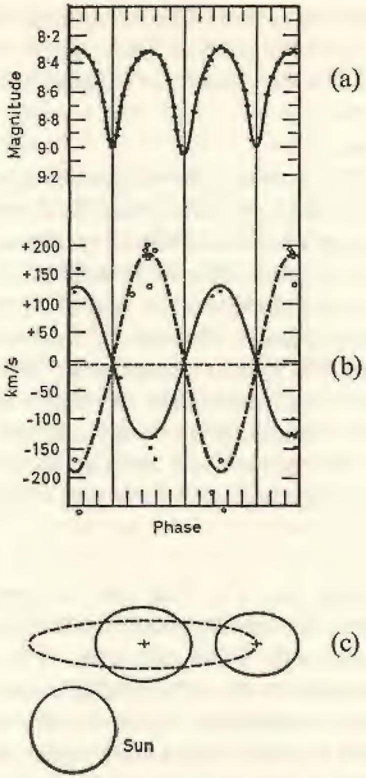


FIG. 17. W Ursae Majoris. (a) light-curve (b) velocity curve (c) diagram of the system.

A0 Cassiopeiae are among the most massive known, although the first is probably slightly greater and they are thus systems composed of supergiants.

Castor (system of six stars). The two components of the visual binary discovered in 1719 are both blue, 2nd magnitude stars with a separation of 3″. Later, a faint red component was discovered at a distance of approximately 72″, the physical connexion of this with the brighter pair is shown by its similar proper motion. The two blue stars are known as Castor A or α_1 Geminorum, and Castor B or α_2 Geminorum and the more distant component is Castor C of magnitude 9·7. Castor A is a spectroscopic binary with a period of 9·2 days and a mass of 3·2 times that of the Sun. Castor B is also a spectroscopic binary with a period of 2·9 days and a mass 2·3

times that of the Sun. The period of the visual pair, α_1 and α_2, is 380 years. Castor C, which in the nomenclature of variable stars is also known as YY Geminorum, is a spectroscopic as well as an eclipsing binary. The period is 0·81 of a day and the light-curve shows two equal minima with amplitude $0^m{\cdot}60$. By combining the spectroscopic and photometric data, the following absolute dimensions of the system are derived: $a_1+a_2 = 1{\cdot}7$ million miles or 0·018 A.U., $r_1 = 329{,}330$ miles or 0·76 $\odot$, $r_2 = 293{,}283$ miles or 0·68 $\odot$, $\mathfrak{m}_1 = 0{\cdot}63\ \odot$, $\mathfrak{m}_2 = 0{\cdot}57\ \odot$, $\rho_1 = 1{\cdot}4\ \odot$ and $\rho_2 = 1{\cdot}8\ \odot$. The surface luminosity of the system is 3·6 magnitudes fainter than that of the Sun.

The spectra of both components are visible, and present uncommon and interesting characteristics. The absorption spectrum of the primary is rather the more intense of the two. Both spectra also contain bright hydrogen lines, and these, like the absorption lines, are subject to periodic doubling. The variations of intensity of the bright hydrogen lines lead us to suppose the existence of a medium in which the rapid orbital motion takes place. This would cause the uppermost layers of the atmosphere of the stars which produce the emission lines, to drag behind. In addition to this, it appears that at least one of the red components of the eclipsing binary is subject to the violent formation of dark and bright spots, which appear and disappear at regular intervals. The light-curve does indeed show rapid irregularities of phase while the spots or spot groups are active, although the periodicity remains constant.

As regards the origin of multiple systems of this type, we can suppose that they are the remnants of a primeval star cluster.

ε **Aurigae.** This system, discovered in 1821, surpasses all other eclipsing binaries in the length of its period which is of 9,888 days, namely 27·08 years. The normal apparent magnitude of the system is about $3^m{\cdot}4$ but at the minimum of its brightness it decreases to $4^m{\cdot}2$. The observed phenomena can be explained as follows (fig. 18). Every 27 years an eclipse occurs which lasts for 2 years. For 6 months the star fades, after which its brightness remains constant for 18 months at half its original brightness, then it brightens again during a second six-month period returning finally to its normal brightness and remaining like that for the next 25 years. Spectroscopic observations also show that the star completes its large orbit in 27 years, but the strange thing is that although only one spectrum is observable outside eclipse, this remains almost unchanged during eclipse and

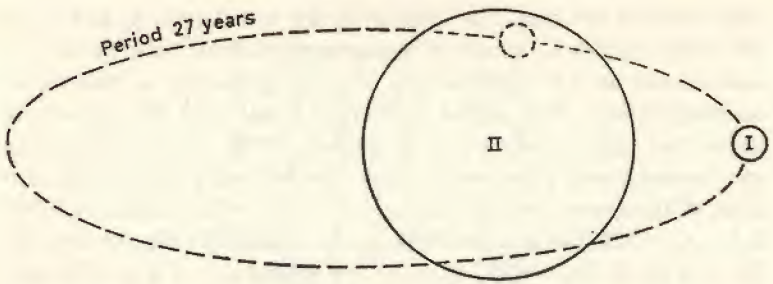


FIG. 18. The eclipsing variable ε Aurigae. Component I is yellow of spectral class F_2 and has a temperature of 6,000° K. Component II is invisible, the temperature is approximately 1,000° K. The inclination of the orbit is 70°.

that there is no appreciable variation of the colour index during the minimum. The position in the orbit at which the eclipse occurs shows that the visible star (I) is being eclipsed by another (II). For these exceptional conditions we can find no explanation among those known for other eclipsing systems. The elements which can be calculated indicate that we are here dealing with two giants, and that the component II must be one of the largest stars known. The diameter of I is calculated to be about 300 times that of the Sun, and its luminosity is 52,000 times that of the Sun. The much larger component II has a diameter of 3,000 times that of the Sun and yet is 2·5 less bright than component I. The diameter of II is so large that its surface temperature cannot exceed 1,000° K, while that of I is about 6,000° K.

We thus have a system consisting of two stars revolving around their common centre of gravity, one star (I) relatively small but very luminous, the other star (II) so large that it could occupy the space between Neptune and the Sun and is composed of extremely rarefied gas of a density of the order of 10^{-9} that of the Sun and has a relatively low temperature. Since the orbital plane of the system is inclined at an angle of 70° to the plane at right angles to the line of sight, star I during the eclipse is never far from the limb of star II, as seen from the Earth. Star II is so tenuous as to be transparent to the radiations of star I, so that the light will pass through star II with little diminution of intensity. A layer of free electrons at the surface of the large gaseous sphere which constitutes star II, absorbs uniformly in all wavelengths a part of the light of the eclipsed star. In other words star II is one of those invisible stars the existence and dimensions of which can only be established indirectly.

In 1953 the atmospheric eclipse had already started, and the phase of constant brightness at the minimum, about one magnitude fainter than the normal brightness, occurred during the middle of December 1955. The duration of this phase is about 330 days. The number of days required for the brightness to reach again a maximum is 192 days, so that the duration of the geometrical eclipse is 714 days, unless exceptional phenomena occur.

Further observations made during the eclipse which began on June 5, 1955, have led to the formulation of new hypotheses on the constitution of this unusual system. Struve and Sahade at Mt. Wilson secured several spectrograms with high dispersion (4·5 Å/mm.) in January, March and April 1957 during the partial phase of the eclipse following the totality. These spectra have been measured and studied by Mrs. Hack. They show a doubling of the lines similar to that which had been observed in 1929, with the violet component which probably originated in a very rarefied envelope surrounding an invisible star. The Doppler displacement towards the violet is clearly measurable and the results obtained by Mrs. Hack for the spectrograms which were obtained during January, March and April 1957 are as follows:

Microturbulence in the envelope	4·4 miles/sec.
Microturbulence in the atmosphere of the F2 star	6·2 miles/sec.
Excitation temperature of the envelope	4,300° K
Excitation temperature of the star	5,700° K

The variations observed in the spectrum can be explained by an excess of ultraviolet radiation in the exciting star, which contrary to earlier hypotheses, could be an invisible star of type B enclosed in an extremely large envelope.

If we assume that $T_B = 20{,}000°$ K and that the difference between the bolometric magnitudes is:

$$M_F - M_B \sim -2$$

then $M_F - M_B \underset{\lambda\ 3,500}{=} -1{\cdot}5$ and therefore the spectrum of the type B star cannot be visible. For $\lambda = 1{,}000$ we have

$$M_F - M_B = +8{\cdot}5$$

For the radius and the ratio of the masses we have:

$$R_B = 621{,}000 \text{ miles} \qquad M_F/M_B = 1{\cdot}15$$

ζ **Aurigae** (fig. 19). Campbell in 1908 noticed that the radial-velocity of ζ Aurigae was variable. This system was discovered later

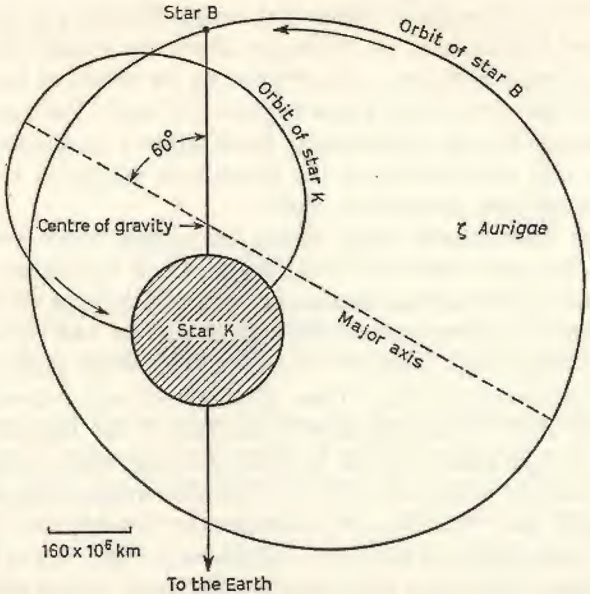


FIG. 19. Orbits of the components of ζ Aurigae in a plane parallel to the line of sight. The two components revolve around the centre of gravity and their positions here correspond to the total eclipse condition. (O. Struve.)

to be both a spectroscopic binary and an eclipsing variable. The composite spectrum proves the existence of two components, the spectral classes of which differ much more widely than is usual in systems of this sort. The primary is a K4 giant, with a temperature of 3,200° K, and the fainter component is a B7 star having a temperature of about 15,000° K. The period is shorter than 3 years (972·15 days), and since the radial velocities of both components can be measured it is possible to derive the linear dimensions of the system. The inclination of the orbit is close to 90°, and the eclipse lasts 40 days, during 37 of which it is total. The semi-major axes of the orbit are respectively $a_1 = 174$ million miles and $a_2 = 348$ million miles. The radii are $r_1 = 200$ ⊙, $r_2 = 4$ ⊙, the masses $\mathfrak{M}_1 = 22$ ⊙, $\mathfrak{M}_2 = 10$ ⊙, and the densities $\rho_1 = 0{\cdot}7 \times 10^{-6}$ ⊙, $\rho_2 = 0{\cdot}08$ ⊙. The apparent visual magnitudes are 4·0 and 6·0 and the photographic magnitudes 5·7 and 5·9. The absolute visual magnitudes are −2·5 and −0·5 and the bolometric magnitudes are −4·6 and −1·4. The discrepancy between the dimensions of the two stars is so great that the blue star may be considered as a dot in relation to the red star,

on the other hand their intensities are equal at a wavelength in the neighbourhood of λ 4200 Å in the violet. These characteristics, and the luminosity of the system, permit us to investigate in detail the distribution of the elements in the atmosphere of a type K giant, when this eclipses a star of class B (fig. 20). Furthermore, two zones

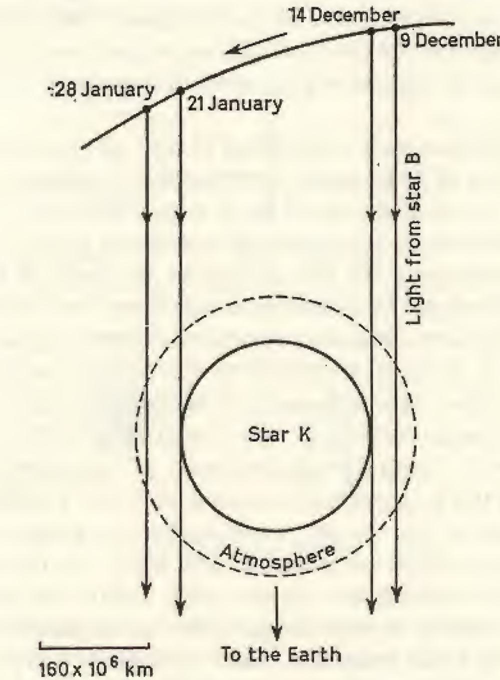


FIG. 20. Phases of the eclipse of the component B of the ζ Aurigae system (1947–1948). (O. Struve.)

can be distinguished in the atmosphere of the type K star, an inner one, comparable with the solar chromosphere, and an extensive outer zone highly rarefied which produces small variations of brightness when it is interposed between the type B star and the terrestrial observer.

Outside the eclipse, ζ Aurigae presents a type K spectrum on which is superimposed one of type B. This is the more intense of the two in the violet, at wavelengths shorter than λ 4200 Å, so that in this region the lines of the Balmer series are always visible. Under these conditions the lines of ionized calcium are not visible. However, with the onset of the eclipse, which is accompanied by a

diminution of magnitude amounting to nearly one magnitude, the H and K lines of ionized calcium, which are characteristic of a red star, make their appearance. Their intensity variation shows that the calcium atmosphere of this star is not uniform but consists of cloud-like condensations suspended in, or above, its chromosphere. It may be supposed that these clouds will occasionally escape from the star, as they do from the Sun, and be lost in space. That this actually happens is suggested by the fact that sometimes, even outside the eclipse, the lines of calcium are observed in the composite spectrum of the system.

These conclusions were established at the eclipses of 1937 and 1940, and at that of 1940 certain chromospheric emission lines were also observed in the spectrum of the K component. The 1947–1948 eclipse was observed by Fracastoro at Arcetri and by McLaughlin at Ann Arbor (Michigan), and that of 1950 by Wellmann at Hamburg. These spectrophotometric observations confirmed and expanded the results that had been obtained at previous eclipses. Fracastoro discovered that at least 10 days before the commencement of the geometrical eclipse, atmospheric lines of ionized metals appeared and that at the same time there was a weakening in the ultraviolet of component B. From his measurements of the intensity of the continuum of the K component in eight different wavelengths, he concluded that at the longer wavelengths the eclipse was predominantly geometrical in character and began on December 15. At the shorter wavelengths, on the other hand, the geometrical eclipse is preceded by a weakening of the continuum of the type B component, due to the extinction of the atmosphere surrounding the K component. Such an effect had been predicted on theoretical grounds by Menzel. Owing to the great difference between the surface temperature of the two components, the amplitude of the minimum is inversely proportional to the wavelength of the radiation employed for the observation. Thus the eclipse is barely detectable in the red while it amounts to two magnitudes in the ultraviolet. It is probable that the K star rotates on its own axis in about the same period as that of the revolution of the system as a whole.

λ Tauri. This is a normal eclipsing variable, with two minima and continuous variation of brightness between eclipses (fig. 21). The variation in brightness at the principal minimum and at the secondary minimum is $0^m{\cdot}35$ and $0^m{\cdot}05$ respectively. The period is 3·953 days. The spectroscopic class of the primary is B3 and that of the fainter

component is K2. The luminosity of the primary is 85% that of the system as a whole. The inclination of the orbit is approximately 70°. As in other systems of the same type, there is a marked effect of irradiation from the primary on the hemisphere of the other component that is turned towards it. The spectral class of this hemisphere is A5, according to measurements made by Maggini with a two-cell photoelectric photometer.

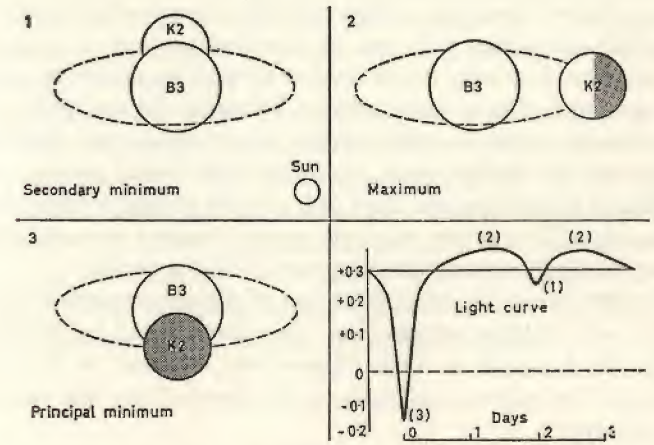


FIG. 21. Eclipsing variable λ Tauri.

VV Cephei. This is an eclipsing binary that combines the characteristics of the two systems namely ε Aurigae and ζ Aurigae already described. It resembles the former in the great size of its primary component, and the latter in the great difference between the spectroscopic classes of its two components. The apparent visual magnitude of the system at maximum is 6·5 and the change in brightness, measured photoelectrically, is $0^m{\cdot}8$. The period is 7,430 days and the two components are respectively of classes M2 and B3. Their masses are 47 ⊙ and 33 ⊙ and their radii 1,360 ⊙ and 56 ⊙ while their mean separation is 4,288 million miles. Superimposed on the changes of brightness due to the eclipse is an intrinsic variation of the red component amounting to about $0^m{\cdot}35$. The spectrum of the binary contains emission lines of hydrogen which vanish during the eclipse, and these transformations during the phase of eclipse have revealed the existence of an extensive atmosphere enveloping the system.

FORMATION OF SYSTEMS OF STARS

A large proportion, perhaps one third, of all the stars are binary or multiple systems of the types which have just been described. It is reasonable to suppose that this fact is connected with the birth of the stars, and that the investigation of the physical characteristics of such systems could throw some light upon their formation.

It is a fact of observation that multiple systems often consist of a relatively close pair, with one or more companions at a greater distance. The close pair, which revolve around the centre of gravity of the system and have short periods, belong to the earlier spectroscopic classes and do not differ greatly from one another. When the components are further apart, revolving with longer periods, they may belong to any spectral class and may be widely different from one another. The orbits of short-period binaries are practically circular, while the eccentricity increases with the period.

The difference of the spectral classes of the components of visual doubles and multiple systems has been investigated by Abetti at Arcetri, by Leonard at Lick Observatory, as well as by other observers. The main conclusions to be drawn from this research are as follows:

(a) If both components of a visual binary are main sequence stars, they comply with the mass-luminosity relationship and therefore the spectral class of the fainter component is usually more advanced than that of the primary. The difference between the spectral classes of the two components is proportional to the difference between their absolute magnitude.

(b) If both components are giants, the opposite is true, that is the spectral class of the fainter component is almost invariably less advanced than that of the primary.

(c) If the primary is a giant or a supergiant, while the fainter component is a main sequence star, the spectral class of the former may be anything from B to M, while that of the latter is the class appropriate to its absolute magnitude, usually less advanced than that of the primary.

(d) The components of a binary system usually belong to spectral classes which are very similar. If these components were single stars of the same absolute magnitude, their spectral classes would differ more from each other. This suggests that the two stars were formed at the same time.

Three hypotheses may be advanced concerning the formation of systems of stars:

(1) The capture of a less massive star by a more massive one. This explanation is not probable on account of the great distances separating single stars, although if the theory of the expansion of the universe is accepted it follows that the star density in space was once much greater than it is now.

(2) The formation of two or more condensations of matter in a primeval nebula from which the system developed. This hypothesis envisages the simultaneous formation of the various components of a binary or multiple system.

(3) Fission of a single star into two or more components. The basis of this hypothesis is the idea that stars rotating rapidly on their axes are at first ellipsoidal and then pear-shaped. Finally they split to form two separate bodies under the stress of strong tidal forces, and further successive splitting may produce other components.

Further observations will no doubt make it possible to confirm, or reject, some of the hypotheses that have been put forward to explain the existence of double and multiple stars.

CHAPTER X

Variable Stars and Novae

We have seen that the variation of brightness of eclipsing variables is due to an external physical cause, so that these stars might more properly be called 'pseudo-variables'. In other classes of variables, however, the fluctuation of brightness is due to intrinsic conditions of the star, though these are still incompletely explained by the study of the simultaneous changes that occur in their spectra. The different types of variables exhibit a wide range of light-curves, but it is not possible to establish sharp dividing lines between one type and another. The fundamental distinction is that between 'regular' and 'irregular variables'. The former have a behaviour which is periodic, so that after a certain lapse of time the light-curve repeats itself identically, while the variation of the latter is produced by some sort of cataclysm in the star itself. The fluctuation of brightness of both these groups is believed to be caused by a disturbance of the state of equilibrium of the star and not by some external agency.

The eleven-year cycle of the sunspots is an example of the cyclic variation to which the Sun is subject. This type of variation, however, is so small that it would be difficult to detect it with available instruments in the case of stars which are far distant. If the total area of all the sunspots at maximum were greater, an observer on another star might be able to detect a diminution of the total brightness of the Sun. The disturbances to which the Sun is subject could be represented as a series of oscillations on either side of a mean value as a function of time but it would remain almost constant throughout the period covered by our observations. In other stars such as the Cepheid variables, we must assume that the whole body of the star is subject to actual pulsations, of sufficient magnitude to affect the spectral class and therefore the temperature. The two principal classes of variables, regular and irregular, can be divided further into

a number of sub-classes. Regular variables include 'short-period variables' with periods from a few hours to two months, and 'long-period variables' with periods from four to five months up to two years. The variables, which show non-periodic changes, are divided into two sub-classes, namely 'irregular variables' and 'new stars or novae'.

All variables are giant stars. Those of short period are among the brightest stars known, of the order of from 100 to 10,000 times the luminosity of the Sun, while the long-period and irregular variables are comparable, in absolute magnitude, with Arcturus or Capella. All spectroscopic classes are represented among variable stars. Short-period variables are found among all the classes from B to M, with a preference for classes F and G. The majority of long-period and irregular variables are red stars of classes from M to S, though a few of these stars are also found among the earlier classes. Novae have spectra which range from nebular to solar type, and possess special characteristics including very marked changes.

The variation of brightness of all variables is accompanied by simultaneous variations of the colour index, of the bolometric correction and of the radial velocity.

Among the regular variables it is found that certain periods are encountered more often than others, from the shortest of about 0·2 days to 1·5 days, 9 days, 80 days and 300 days. Among these groups there is a progressive modification of the shape of the light-curve with period. With increasing period, the curve becomes increasingly asymmetrical. Stars of the two shortest periods have a high space velocity, which decreases with increasing period and then begins to increase again among those of longer periods. The spectral class of stars with periods longer than one day likewise changes progressively with period.

MIRA CETI VARIABLES

Long-period variables are often referred to as Mira Ceti type variables or *o* Ceti variables, named after the type star. The class is not sharply defined, owing to the difficulty of interpreting the light-curves and the radial velocities of the stars. Bearing this in mind, we can include in this class stars which have periods longer than 40 days and which are neither eclipsing variables nor Cepheids. These stars have spectra which belong to class G or to more advanced classes,

and which are very similar to those of giants often with emission lines. We know the periods of approximately 2,000 stars of this class and for these the ephemerides are given yearly. About 500 of them are brighter than magnitude 10 at maximum, and for these we have a considerable quantity of photometric and spectroscopic data. The subdivision of the long-period variables into sub-classes is based on the diversity of the light-curves which they exhibit (fig. 22). Various

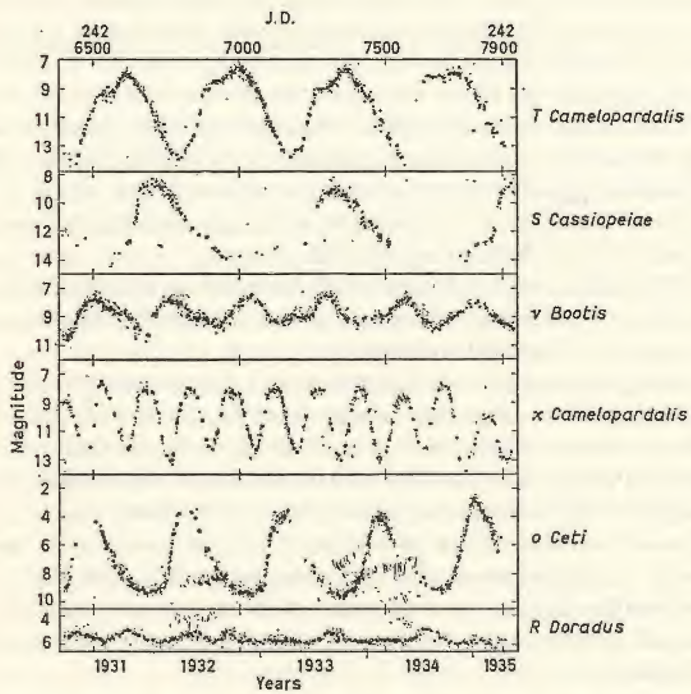


FIG. 22. Light-curves of six long-period variables.

attempts to classify them on this basis have led to the recognition of three fairly well defined groups. In the first, the rise to maximum brightness is much more rapid than the fall to minimum, and the minimum itself is wider than the maximum. In the second, the light-curve is more or less symmetrical, and in the third group the section of the curve between minimum and maximum shows a relatively flat section or even a hump or a secondary maximum.

Among all these stars, successive maxima and minima may differ

one from another by one or more magnitudes, and two curves of precisely the same shape are practically never encountered.

Among the long-period variables, and also among the Cepheids, there is a well-defined relation between period and spectral class, as we shall see later. Those which have longer periods are associated with more advanced spectral classes as well as with magnitude variations of greater amplitude. Thus the stars of this type range from class M0, with emission lines with periods of about 150 days and with amplitudes of about three magnitudes to class M8, with periods of 500 days and with amplitudes of five magnitudes. The mean absolute magnitude of variables of the Mira Ceti type is about -2 for those with periods of 150 days, decreasing to $+0{\cdot}3$ magnitude for those with a period of 350 days. The diameters range from 100 to 200 times that of the Sun and that of *o* Ceti is 300 times that of the Sun.

Mira was discovered to be variable by Fabricius in 1596 but thereafter it faded into invisibility and it was only many years later that its variations were recognized to be periodic, and followed with the aid of a telescope. Its apparent visual magnitude varies from 2 to 5 at maximum and from 8 to 10 at minimum. The period is not constant (fig. 22), but varies around 330 days. It is a red star, and the radiometric observations of Pettit and Nicholson have shown that its temperature varies from 2,600° K at maximum to 1,900° K at minimum.

Its spectrum is in general of class M6 at maximum and M9 at minimum, but is complicated by marked changes throughout the course of the cycle. Many atomic and molecular absorption lines are visible, the most important of the latter being those of titanium oxide. Emission lines of hydrogen are also present, though the $H\epsilon$ in the violet is characteristically absent, being obscured by the intense H line of ionized calcium.

From the appearance of the spectrum, and the changes to which it is subject, Joy has concluded that it is composite, the spectrum of a tenth magnitude B type component being superimposed on the common M type spectrum of supergiants. The existence of this component was confirmed visually by Aitken. According to Struve, Mira Ceti, like the eclipsing variables, must be considered as a double star in which the fluctuation of brightness of the very large red primary is partly caused by its expansion and contraction, but is primarily the result of the formation and dissipation of dark absorbing clouds in its vast atmosphere. The brightness of the small

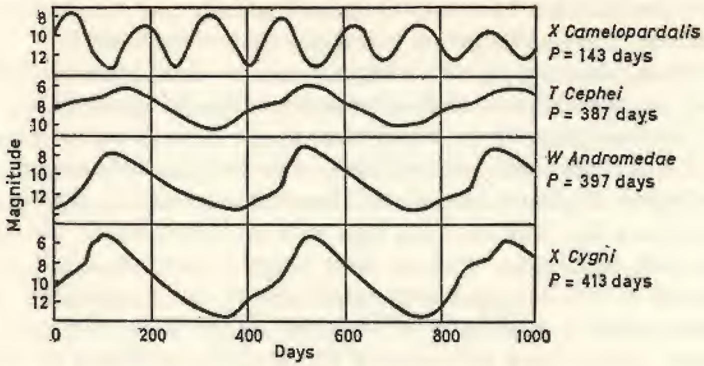


FIG. 23. Light-curves of four long-period variables of spectral class Me.

blue companion varies with a period of 14 years, probably as a result of its eccentric orbit and of its eclipse, once in every revolution, by the extensive obscuring atmosphere of the primary.

CEPHEIDS

Under this name, derived from the type star δ Cephei, is gathered an important and varied group of stars which, though it cannot be precisely defined, nevertheless shows certain characteristic features. A variable is to be classed as a Cepheid if it has a regular period shorter than 100 days, a variable spectrum and cannot be included in the class of long-period variables. Included together in the same class, therefore, are Cepheids of relatively long period and others with periods which may be even shorter than one day but which, nevertheless, have unquestionably similar characteristics. Nowadays about 350 long-period Cepheids have been discovered in the Galaxy, and 2,500 in the Magellanic Clouds and other galaxies. About 1,500 short-period Cepheids are known, of which over 600 are situated in globular clusters (see p. 205).

The Cepheids so far discovered can thus be arranged in a sequence ranging from those having at maximum a spectrum of class B8 and periods of 0·06 of a day to those of class M with a period of 79 days. The progressive changes of the spectrum along the series from short to long period are continuous and regular. This period-spectrum relation constitutes the main similarity between Cepheids and long-period variables, and is probably due to the accompanying variations

of mean density or to some other dynamic gravitational cause. The light-curves, although they are for the most part asymmetrical, are very regular, and differ little from one cycle to the next. The rise to maximum brightness is usually very rapid, with a sharp maximum, followed by a slower diminution of brightness, and a much wider minimum. Since it was observed that the periodic light variations of these stars were accompanied by variations of radial velocity with the same period, it was at first thought that they were stars similar to spectroscopic binaries. Indeed the orbits were calculated exactly as if they were binary systems. It was soon discovered that the positions of their periastra were around 90°, and therefore that it was very unlikely that all their orbits would have the same orientation relative to the line of sight. The observed relation between period and density was also difficult to explain in terms of a binary system, and finally the calculated linear dimensions of the hypothetical systems revealed a geometrical impossibility in the orbits, since the distance a_1+a_2 of the two components was less than the radius of the primary itself and the fainter component would thus actually be inside the primary. Other explanations therefore had to be sought, and the most plausible of these considers a Cepheid as a star which is pulsating.

The general shape of the light-curve has an amplitude rarely exceeding 1·5 magnitude, and is closely related to the period. The curves of those Cepheids which have periods of about two days are symmetrical and the amplitudes are small. With increasing period the amplitude increases and the rise to maximum becomes steeper. In the case of Cepheids which have a period of 7 days a secondary wave or a hump develops on the descending section of the curve. For Cepheids which have a period of 10 days the curve is symmetrical, its shape around the maximum has a very sharp hump almost like a point, and for those which have a period of 15 days the amplitude increases considerably, while the ascending section of the curve becomes steeper and shows a marked inflexion. When the period is larger than 20 days the curves are regular once again, with rapid rises to maximum and large amplitudes. The curves which we have described are those derived from visual observations; photographic curves are similar, but on average their amplitudes are 50% greater. The reason for this is that these stars are much redder at minimum than at maximum as is also shown by the variations of their spectra.

Towards the end of the last century, many variables with periods

of about 12 hours were discovered photographically in the globular clusters. These clusters consist of very large numbers of faint stars, concentrated at the centre of the system, like the well-known example in the constellation of Hercules. Since the variables belonging to a given cluster must be virtually at the same distance from the observer, and since their mean apparent magnitude is also practically the same, it follows that their absolute magnitude must likewise be the same in all cases. If now we observe variables of the same type in another cluster, we may assume that, being of the same nature, it will have the same absolute magnitude, and that therefore the difference in apparent magnitude will be due simply to the difference of the distance of the two clusters from the Earth. Extending these investigations to the Magellanic Clouds, Miss Leavitt of Harvard Observatory detected a large number of variables with periods ranging from 15 hours to over 100 days which had light-curves characteristic of the Cepheids. Furthermore Miss Leavitt established the fact that there is a close relation between the apparent magnitudes and the periods of these stars, in the sense that stars of a given apparent magnitude have the same period. Since the stars in question belong to the Magellanic Clouds, they can be considered to be all at the same distance from the Earth, and therefore the above statement will also be true if we consider absolute instead of apparent magnitudes. Later, from the observations of Shapley, it was possible to construct a curve showing the variation of period as a function of absolute magnitude, although there is some uncertainty with regard to

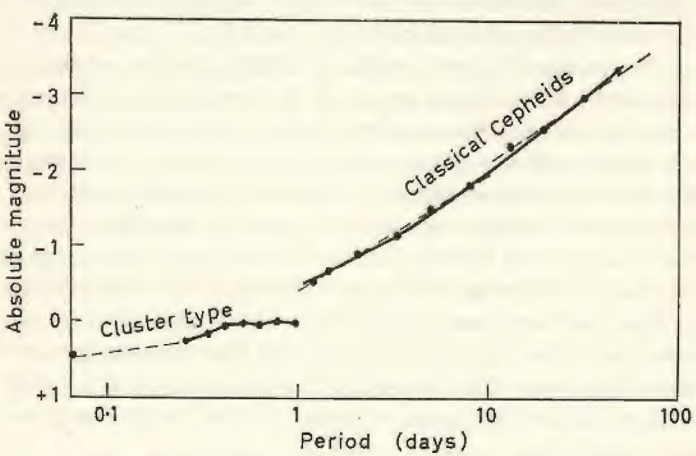


FIG. 24. The period-luminosity relation for Cepheids.

the position of the 'zero point'. We must admit that this curve is not a simple one. The Cepheids of the globular clusters in fact belong to population II, and since we know the absolute magnitudes of RR Lyrae variables, which are Cepheids with periods less than one day and belonging to population II, it is possible to plot the curve shown in figure 24. Besides these stars, there are also those we know as 'classical' Cepheids like δ Cephei, which are found in the spiral arms of the Galaxy. These stars belong to population I, and are intrinsically brighter than the Cepheids of population II. These must presumably occupy the shaded curve shown in figure 25, which is parallel to the curve for Cepheids of population II, but displaced from it by about 1·5 magnitudes towards the top of the diagram.

There is a group of stars with very varied characteristics which constitute a transitional stage between Cepheids and the red, long-period variables. Their periods range from 20 to 150 days, their

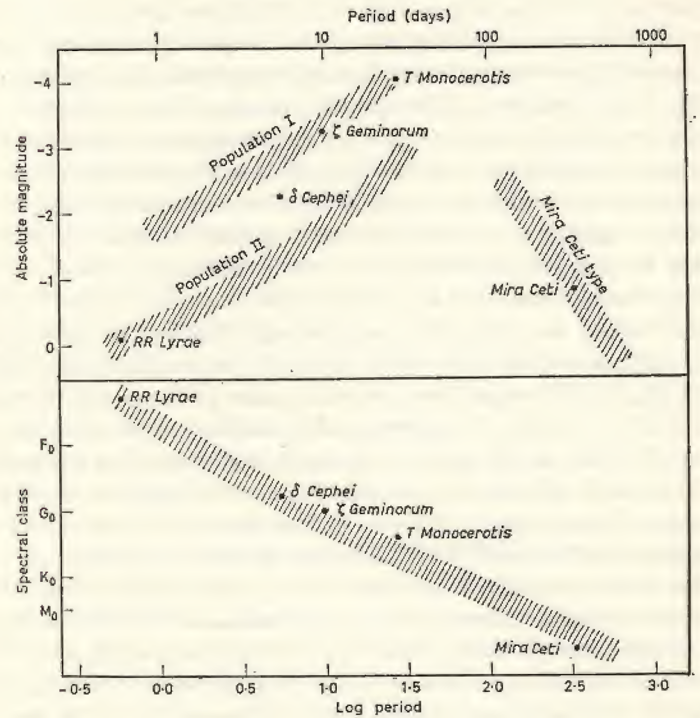


FIG. 25. Relation between periods, absolute magnitudes and spectral classes of Cepheids of population I and II.

variations are cyclic rather than periodic, and their light-curves are less regular than those of the Cepheids. Stars of the RV Tauri type belong to this group. RV Tauri varies in a semi-regular fashion over a period of 79 days. In each period it passes through two more or less equal maxima and two unequal minima. Its spectrum belongs to class K and varies considerably between maximum and minimum, as in the case of the Cepheids. Stars of the RV Tauri type are also members of population II, as are the Mira Ceti-type variables which have a period of less than 200 days.

A high space-velocity is a characteristic of stars of population II, while the classical Cepheids of population I are low-velocity stars.

Together with the variation of the light emitted by a Cepheid we observe a variation of its spectrum and of its radial velocity. Both these are extremely interesting since they suggest various hypotheses regarding the phenomena occurring on these stars. The spectral lines and the energy distribution throughout the spectrum show that the temperature of these stars is higher at maximum than at minimum. The variation is continuous throughout the photometric cycle, and the greater the variation in luminosity, the greater the changes that occur in its spectrum. The spectral change from maximum to minimum is from an earlier to a later spectral class, and hence the hydrogen lines and the enhanced metallic lines belonging to ionized elements are more intense at maximum than at minimum. The lines of the arc spectrum, on the other hand, present smaller variations. It may be said that in general the spectral variations amount to one or two classes, from G to K, or from F to K, or from G to M. The radial velocity also appears to vary during the period of light variation, with an amplitude which is proportional to that of the light-curve (fig. 26). The maximum negative value of the radial velocity, that is of the velocity of approach of the surface of the star, occurs at, or very near to, the time of maximum brightness. The maximum positive radial velocity, that is of the velocity of recession, occurs at the time of minimum brightness, so that the radial velocity curves reproduce in reverse all the peculiarities of the light-curves.

The most plausible theory that has, at the present time, been proposed to explain these complex phenomena, is that which regards the Cepheids as pulsating stars, periodically expanding and contracting. According to this theory, the varying radial velocity represents the actual approach and recession of the surface of the star to the observer. Shapley, Eddington, Tiercy and others have attacked this problem from the viewpoint of thermodynamics, in an attempt

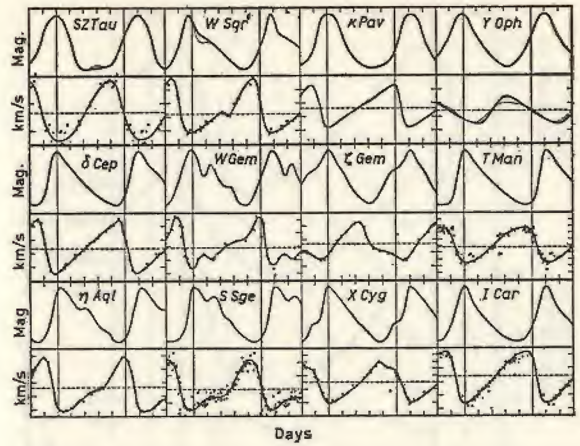


FIG. 26. Comparison between light-curves (above) and velocity curves (below) for some Cepheids. (Payne and Gaposchkin.)

to demonstrate the existence of such a pulsation and to explain how it could be maintained and renewed periodically with such rapidity. In a normal star it is assumed that the weight of the outer layers is balanced by the weight and the pressure of radiation of the incandescent gases which constitute the internal layers. If for any reasons, as for instance the excessive development of subatomic energy, this equilibrium is disturbed, an increase of the pressure of the gases will cause the whole gaseous sphere to expand. This will continue until a certain limit is reached, a limit which is determined by the recession of the star's material from the centre of gravity or by its inertia. Thereafter the pressure of the internal gas will be insufficient to maintain the equilibrium and the external layers will fall back towards the centre of the star once more.

The initial disturbance would thus set up a kind of tide around the position of equilibrium of the star which would reveal itself by variations of brightness, of ionization, hence spectral changes, and by variations of radial velocity. Theory shows that the magnitude, and therefore the period, of such a pulsation must be inversely proportional to the square root of the density, and must also be subject to the law which states that the decrease of the volume of a gas will produce an increase in its pressure. The behaviour of the pulsation of a short-period Cepheid, such as δ Cephei, as exhibited by its variations of brightness, temperature, spectral type, radial velocity and radius is shown in figure 27. It will be noted that the

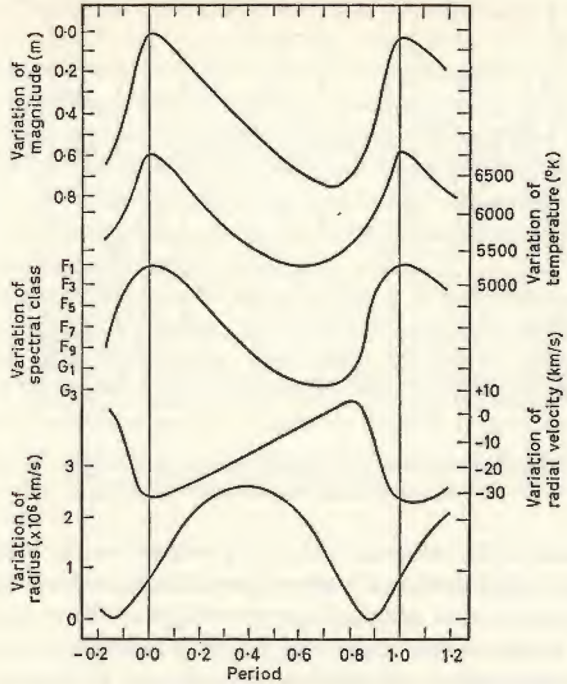


FIG. 27. Variations of magnitude, temperature, spectrum, velocity and radius of δ Cephei. (Becker.)

radius reaches a minimum value slightly before the maximum of brightness and of temperature, and that it reaches a maximum value before the temperature and brightness are at a minimum (see also fig. 28).

Both qualitatively and quantitatively the theory of stellar pulsation is capable of explaining the observed phenomena, including the lagging of the maximum luminosity of the star behind its minimum of size. On the other hand, the period-luminosity relation, which must be associated with the dimensions of the star, still remains to be explained.

In order that a Cepheid should not explode, it is necessary that its pulsation, namely the increase and decrease of its volume, should be only a fraction of its whole volume. This is in effect what is observed. Tiercy has calculated that if the mean radius of SU Cassiopeiae is approximately 4 million miles, then the radius varies from 4·2 million miles at maximum to 3·9 million miles at minimum.

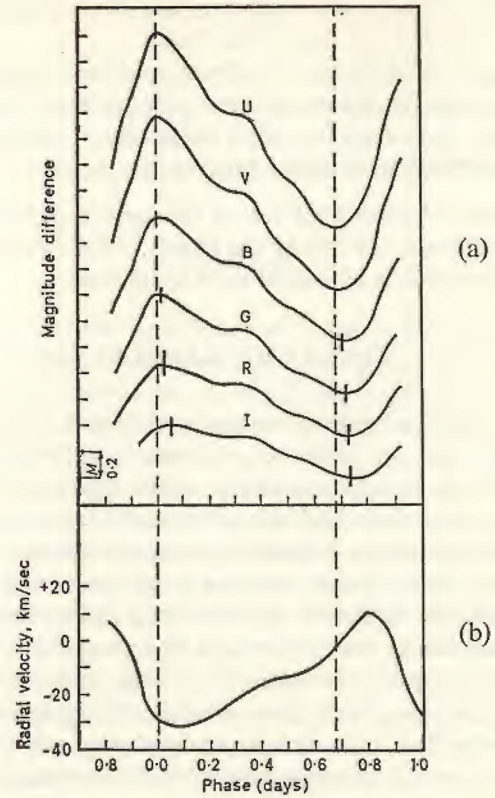


FIG. 28. Cepheid η Aquilae. (Stebbins.) (a) light-curves for various colours. (b) velocity curve.

This gives an overall variation of 8%. δ Cephei, with a mean radius of 14 million miles, shows a variation of 1·6 million miles between maximum and minimum radii, or 9%. These variations are of the correct order of magnitude.

Below are given data for some of the better known Cepheids.

RR Lyrae. Period P = 0·57 of a day; maximum and minimum apparent magnitudes 7·1 and 7·8; spectrum varying from class B9 to F2; absolute magnitude −0·1; radius $r = 3{\cdot}5$ million miles; mass $\mathfrak{M} = 3{\cdot}5$ times that of the Sun; density $\rho = 0{\cdot}007$ times that of the Sun.

δ Cephei. P = 5·37 days; maximum and minimum apparent magnitudes 3·7 and 4·5; spectral class varying from F5 to G2; absolute

magnitude $-2{\cdot}2$; $r = 16$ million miles; $\mathfrak{M} = 7$ times that of the Sun; $\rho = 0{\cdot}0004$ times that of the Sun.

l **Carinae.** P = 35·52 days; maximum and minimum apparent magnitudes 3·6 and 5·0; spectrum varying from class F8 to K0; absolute magnitude $-5{\cdot}1$; $r = 50$ million miles; $\mathfrak{M} = 50$ times that of the Sun; $\rho = 0{\cdot}00005$ times that of the Sun.

For these and other Cepheids of the same type the product $P\sqrt{\rho}$ is almost constant, confirming the results of the theoretical investigations of the physical constitution of these stars.

RV TAURI VARIABLES

Among the various types of regular and irregular variables must be numbered some stars which may be termed 'semi-regular'. RV Tauri, which we have already mentioned, is the type-star of this class of variables. Although the individual members of this class exhibit very diverse characteristics, in general, it may be said that their variation in brightness is continuous and that the minima are alternately deep and shallow. The difference of intensity of two successive minima is variable, so that in the course of a few years these become interchanged. The maximum is slightly variable, and other irregularities in many cases complicate the variation of brightness to a marked degree. Under these circumstances we cannot speak of a true period, although we may measure the interval of time between two successive minima of the same sort, that is alternate minima, which often exceeds 50 days. The majority of the stars of this group are of class M.

Another considerable number of variable stars belonging to the more advanced spectral classes are irregular. These are for the most part giants or supergiants of classes M or N. Typical of this class is *X* Herculis, whose apparent magnitude varies from 5·8 to 7·2 and whose spectrum of class M contains emission lines. Its brightness varies continuously between these two limits and appears to follow no law. Both the level of maxima and minima, and the interval of time separating them, are variable. A period of about 100 days appears to be the most common, but it is not persistent and is interrupted by irregular variations and by periods of constant brightness lasting several months. Some of the stars which have high intrinsic luminosity and low density, such as α Orionis and α Herculis, are irregular variables. The cause of their variability is unknown. It is

possible that they are also pulsating stars, but non-periodic in character.

The investigation of the spectra of these stars, and especially of the intensity of their absorption bands, will throw some light on the nature of their light variations. Both the light variations and the spectroscopic characteristics present certain analogies with novae.

NOVAE

If the breakdown of the equilibrium of a star or the disturbances of the type that appear to have been established in the case of the Cepheids are very deep-seated, a cataclysmic explosion will occur in the interior of the star which will convulse its whole body. After the critical phase of the phenomenon has passed, the star can return to a state of more or less stable equilibrium. This is what happens in the case of novae, which may be regarded as irregular variables. Long-period variables and novae, in fact, represent a continuous sequence, if we assume that the light variations of a nova have a very long period when compared with the length of human life.

To call a star a 'nova' is not to imply, as the name would suggest, that the star appeared where before there was none. In the majority of cases, as modern methods of observation increasingly demonstrate, before the appearance of a nova, that is of a star so bright as to attract general attention, there was, in precisely the same position in the sky, a very faint star. This was perhaps barely visible or just within the reach of photography with the largest telescopes and did not show any exceptional characteristics. This, however, can only be affirmed with reserve, since we still have very little information about the constitution of these stars before their explosion. Owing to their faintness we usually know nothing about their spectra, which alone are capable of telling us something about their history. It seems that before the cataclysm the star is slightly variable and of a normal spectroscopic class, usually A, F or G.

The nova phenomenon consists of an extremely rapid increase of brightness (fig. 29) such as, for instance, that of Nova Lacertae 1936, the brightness of which increased ten thousandfold in less than twelve hours. The brightening of Nova Herculis 1934, on the other hand, was by comparison relatively slow. Photographic plates which had been obtained before the outburst show it to have been of magnitude 15·5, and its transition from magnitude 3 to magnitude 1 was

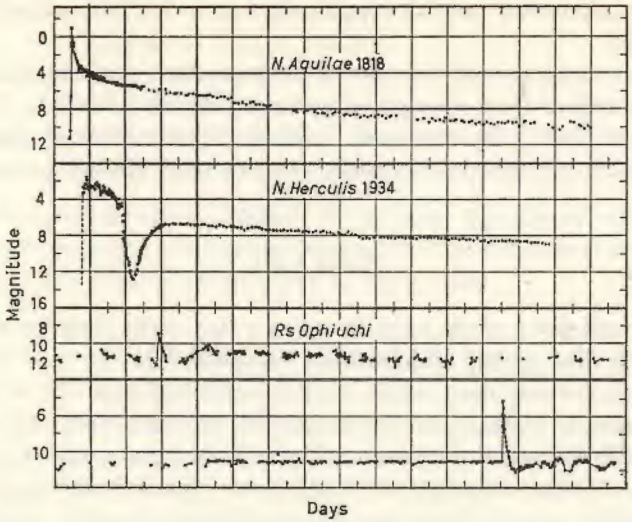


FIG. 29. Light-curves of Novae.

observed to take nine days, while Nova Pictoris, which appeared in the southern celestial hemisphere in 1925, increased in brightness from third to second magnitude over a period of six weeks. After a rapid brightening, a nova returns slowly to its original magnitude where it continues to vary within a small amplitude.

The most spectacular novae are those which appear in our own Galaxy, because being relatively near to us they are extremely brilliant at maximum. The same phenomenon is also to be observed in other galaxies and such stars are known as 'extragalactic novae'. Various methods of evaluating the distance of galactic and extragalactic novae have established the important fact that the majority of them have an absolute magnitude of about −7, that is to say they are 60,000 times brighter than the Sun. Among the galactic novae some were thought to have exceptional brightness, which might be attributed either to their small distance from us or to their exceptional dimensions and absolute magnitude.

The systematic programme of observations begun a few years ago at the Mt. Wilson Observatory has established the existence of stars, to which the name 'supernovae' has been given. These have the characteristic of reaching an absolute magnitude of −14 at maximum, that is to say, an intrinsic luminosity one hundred million times greater than that of the Sun. This conclusion is based on observations of

galaxies which represent a much vaster field of investigation than our own Galaxy. Nevertheless, supernovae do occur within the Galaxy, and the likelihood of observing them depends solely on the frequency of their occurrence. The famous nova of 1572 may have been such a supernova. The absolute magnitude of a supernova is, on average, of the same order as the mean absolute magnitude of the galaxy in which it appears, and hence the supernova phenomenon is of great importance in the study of the constitution of the galaxy. When the frequency of novae and supernovae is plotted as a function of their absolute magnitude at maximum, a curve is obtained with two maxima at −7 and −14 magnitudes, with a well-defined minimum such as is encountered between the giants and the dwarfs of spectroscopic class M. In the phenomenon of the stellar explosion we find thus a similarity with what happens in the normal stellar evolution.

In order to investigate the physical processes involved in this extraordinary phenomenon, which is one of the few occurring during a period which is very brief compared with the time-scale of cosmic phenomena, it is essential to study the spectra of novae and supernovae, and the changes that they undergo during the most violent phases of the outburst.

This has been achieved in recent years, particularly in the case of galactic novae whose great brightness has made it possible to photograph and study their spectra under high dispersions and with increasingly perfected technical means. Thus, for instance, extensive and interesting series of spectra were obtained of Nova Aquilae 1918, which was the brightest nova that had appeared during the last three centuries, and also of Nova Herculis 1934. These spectrograms, obtained during the most critical phase of the outbursts, make it possible to develop plausible theoretical interpretations.

The spectrum of Nova Aquilae before and at its maximum brightness was similar to that of a normal white star, but with its absorption lines displaced towards the violet. This may be explained by supposing that the outer atmosphere of the star was expanding towards us with the explosive velocity of about 930 miles/sec. along the line of sight. Immediately after maximum, wide emission bands of hydrogen made their appearance, showing that an extensive envelope of this gas was moving away from the central nucleus of the star with an even greater velocity, of the order of about 1,550 miles/sec. As this envelope continued to expand and to become less dense, the hydrogen bands began to disappear, their place being taken by others which

are equivalent to the 'forbidden lines' of oxygen and nitrogen which can only be produced in environments of extremely low density. One year after maximum, the spectrum was virtually continuous, with few forbidden bands, and was being produced by the stellar nucleus. A year later these bands had disappeared completely. After the explosion, the star must have collapsed suddenly, finally becoming less bright than it was just before the outburst. The higher temperature, and therefore greater brightness of its surface compensates for its contraction, so that the actual brightness remains about the same.

A phenomenon which is rarely observed in novae was shown by Nova Aquilae several months after maximum. A faint circular nebulosity was observed to surround the star, and with the passage of time this was seen to be slowly expanding. Since 1922 this nebulosity has been increasing in size at the rate of 2″ per annum. Combining this value with the velocity of expansion as measured spectroscopically, the distance of the nova is found to be 1,200 light-years. At maximum, Nova Aquilae must have reached a brightness 300,000 times greater than that of the Sun, the greatest brightness so far recorded for normal novae.

The spectroscopic observations of Nova Herculis 1934, which were possible from the critical moment of outburst onwards and were made at many observatories, led to similar results. At its maximum brightness the spectrum was similar to that of a class A star, though in addition there were wide emission bands superimposed on the continuum. Something similar is to be observed in the spectra of other celestial objects, namely in those of variable stars and nebulae, or in that of the limb of the Sun during the moments immediately preceding and following the total phase of a solar eclipse. In the case of the Sun, as has already been explained, this is due to the fading of the light of the photosphere which allows the emission lines of the chromosphere, that is of the upper layers of the Sun's atmosphere, to become visible. The width of the emission bands and absorption lines, as also their position, are interpreted as being due to the velocity of the motion of the gases from the interior of the star towards the exterior. In the case of Nova Herculis, the greatest velocity measured was about 249 miles/sec. Later, when its brightness was considerably reduced, the continuous spectrum faded out, leaving only the bright bands. The spectrum then resembled that of the gaseous nebulae and of the hottest stars, though with certain features suggesting that the star underwent periodical outbursts. During one of these, in the summer of 1935, it was discovered that the star had

split into two. The two components, which at that time were very close to one another, gradually separated and two nuclei appeared which had spectra similar to that of nebulae. We can see that in the case of these two novae the explosion has given rise to two very different situations.

In the case of Nova Herculis a few years after the great explosion (1939–1940), it became clear that what we had thought to be two stellar nuclei were, in effect, the loops of a gaseous condensation which was expanding at the rate of 0″·6 per annum. The presence of a nebulosity in emission around the 'ex-nova' was shown by spectroscopic observations. These reveal the presence of hydrogen lines and of ionized oxygen (OII and OIII). Like so many other ex-novae, *DQ* Herculis 1934 at the minimum shows fluctuations of brightness. The photoelectric study of these fluctuations carried out by Walker in 1954 shows that this star is a binary of Algol type, having a period of 4 hours 39 minutes, a partial eclipse lasting one hour and variations in brightness of one magnitude. This star, therefore, is the fastest eclipsing variable so far known. Later photographs taken by Rosino show that this star is embedded in a very small and very dense luminosity which surrounds also a companion of 16th magnitude, at a distance of 3″·5. Whether this companion is connected physically or only optically to the nova, it is not yet known.

The nebulosity is expanding with an angular velocity of 0″·33 per annum. The comparison of the radial velocity and the yearly angular velocity of the expanding envelope gives for this system a distance of 200 parsecs. Its magnitude, when not in the eclipse phase, is 7·6.

Observations, which were made in several radiations, show that the occulting star is the redder of the two.

Further observations by Walker in 1955 and 1956 indicate that the light-curve determined by the eclipse has changed shape and depth between 1954 and 1956, so that the photometric elements of the system are uncertain. Walker has also found evidence of periodic variations of brightness of the star lasting one minute, and this indicates how complex this particular system must be. In order to explain the short pulsations of one minute, it has been suggested that either the star as a whole, or a determined area of the system is pulsating.

The changes observed in the spectra of novae are of great importance to an understanding of the events occurring at and after the explosion. These changes vary from one nova to another, and it is

clear that the general trend for stars of this kind is very similar and can be followed through a succession of various phases.

Summarizing what has already been said of individual novae, we may say that the small quantity of evidence as yet available indicates that their spectra during the pre-explosion phase contain a system of absorption lines similar to those of class B, together with emission bands. As the nova approaches the maximum, its spectral class changes to A. At about the time of maximum, new absorption lines appear in addition to the emission bands, so that the class advances from A5 to F8. After the explosion, wide and diffuse lines of hydrogen and of ionized metals make their appearance. These lines are considerably displaced, owing to high radial velocities, and after increasing in intensity to a maximum, they begin to fade again and finally disappear. During this phase, lines of neutral helium, oxygen and ionized nitrogen also appear, while the hydrogen lines develop a multiple structure. While these lines are increasing in intensity, other lines and bands characteristic of the Wolf-Rayet stars (p. 50) make their appearance. These are for the most part due to doubly ionized nitrogen.

With the progressive development of the nova, all the absorption lines gradually disappear with the fading of the continuous spectrum, while the bands typical of planetary nebulae slowly develop. These remain for a long time, and only fade very slowly. The continuous spectrum and the Wolf-Rayet bands then reappear. So far as we know at present, therefore, the spectrum of a nova after its outburst resembles that of a Wolf-Rayet, and is often intense in the ultra-violet region.

As long ago as 1885, a nova was discovered in the Andromeda Nebula. It reached apparent magnitude 7 and therefore was one-tenth of the brightness of the nebula as a whole. At that time little could be deduced from the observations, but with the ever-increasing improvement of photographic observations, about twenty novae have since been detected in the Andromeda Nebula. All of these were fainter than the 1885 object, which therefore appears to have been exceptional, with a brightness at maximum which was many thousand times greater than the others. From this it must be concluded that it was a supernova and subsequent observations have supported this conclusion. Novae and supernovae may appear in the same galaxy, but their frequency is very different. A systematic search undertaken jointly by the Mt. Wilson and Mt. Palomar observatories has led to the detection of many novae and supernovae and to the classification

of these objects. Since 1885, forty supernovae have been discovered in thirty-six different galaxies and twenty-two of them have been detected since 1937, when this systematic research was initiated with the study of more than 300 galaxies brighter than magnitude 15. These may be regarded as a fair sample of the region of the universe that can be explored by today's largest telescopes, and in this way it is possible to gain some idea of the frequency of supernovae.

It seems that one supernova may appear every 600 years or so in any galaxy, irrespective of its type. Accepting the figure of 30 novae per annum in the Andromeda Nebula, it would appear that the frequency of supernovae is some 20,000 times less than that of ordinary novae. It is likely that with the development of more powerful Schmidt telescopes than those at present in existence, it will be possible to detect up to twenty supernovae a year. The fact that these stars appear in galaxies of all types, that is presumably without preference for any particular stage in their evolution, suggests that the instability which is the cause of the explosion is not related to any particular moment in the life story of the galaxies. The hypothesis has been put forward that normal novae may be the explosion of dwarf stars, while supernovae may be the explosion of giants.

Although the investigations relating to supernovae are still in their infancy, it appears to be possible to classify them into two different types. Supernovae of the first type have light-curves which are generally similar to those of normal novae. When they explode, their luminosity increases a millionfold or more in the space of a few days. On average their brightness at maximum, which is of the order of one hundred million suns, is comparable with that of a whole galaxy of average size. The brightness of these supernovae decreases rapidly once the maximum has been attained, then, after some weeks, more slowly, fading by one-third every month.

The supernova discovered in IC 4182 by Zwicky at Mt. Wilson in August 1937 is characteristic of this type. IC 4182 is a dwarf galaxy situated at a distance of about three million light-years from us, and the supernova attained its maximum brightness on August 22, when its apparent magnitude was 8·2, which, given the distance of the galaxy, is equivalent to an absolute magnitude of —16·6 (fig. 30). This is the greatest luminosity of any supernova yet observed, being equal to six hundred million suns, or one hundred times that of the entire galaxy containing it. The first spectrogram of this supernova was obtained on August 30, and others were recorded for about a

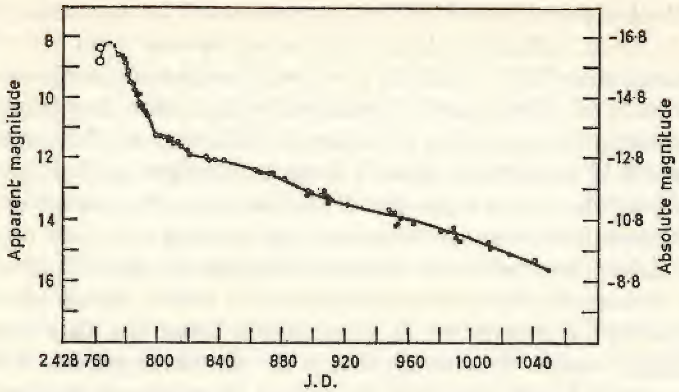


FIG. 30. Light-curve of the Supernova in IC 4182.

year, thus providing a complete picture of its spectral variations. The star was still within the reach of photography two years after its discovery, at which time it was about five hundred thousand times fainter than at maximum (Plate 10).

The imposing scale of this extraordinary phenomenon will be appreciated when it is realized that in one day this supernova radiated as much energy, in the region of the photographed spectrum, as the Sun has radiated in one and a half million years. The study of the spectra is extremely difficult, but it is clear that we are dealing here with phenomena which are still more complex than those studied in the spectra of novae. The chief characteristic noted is the very great width of the emission bands which, unlike those in the case of novae, appeared suddenly at maximum showing that there are fundamental differences between the nova and the supernova explosion. The continuous spectrum is only just visible, and the velocity of expansion of the gases as deduced from the width of the bands varies between 2,800 and 3,750 miles/sec. Furthermore, the unusual phenomenon was observed of a gradual shift of the whole violet region of the spectrum towards the longer wavelengths. There is nothing analogous to this in the spectra of novae. No such red-shift is detectable in the visible region of the spectrum, but the changing composition of the spectra suggests changes in the ionization levels. The only features of the spectra that can be identified are two relatively narrow bands of neutral oxygen which appear five or six months after maximum.

The second group includes supernovae which at maximum have a luminosity of the order of ten million suns, and whose light-curve

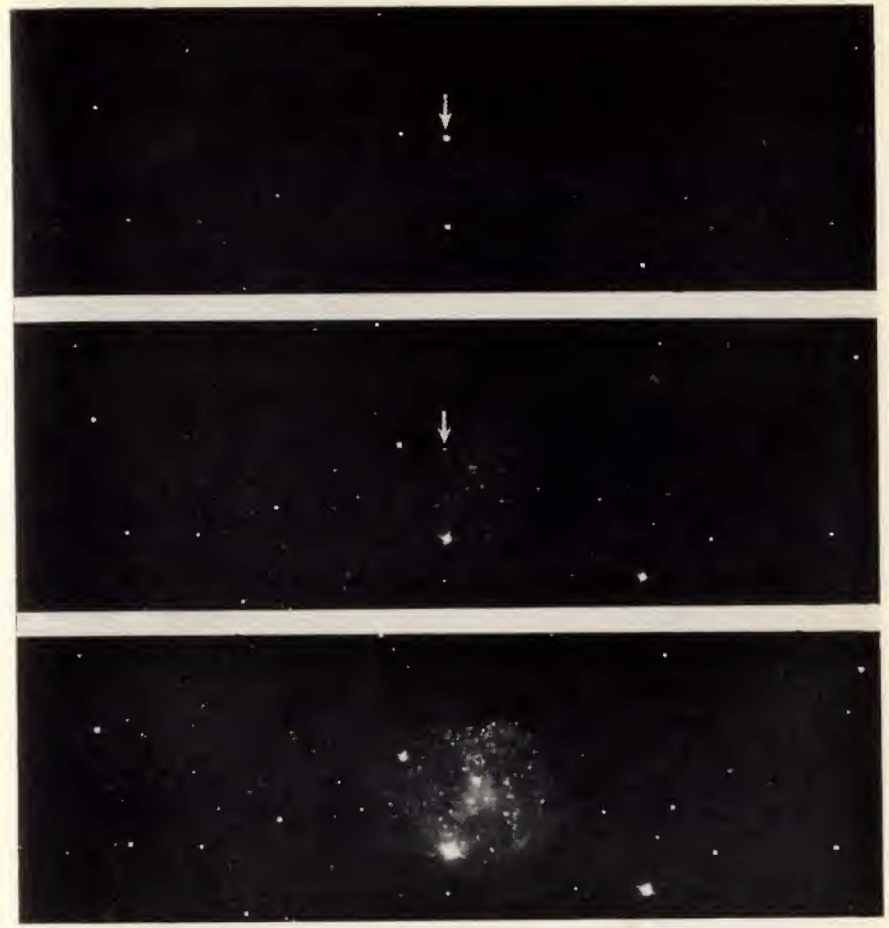


Plate 10. Supernova in IC 4182: 100-inch photographs. Mt. Wilson and Palomar Observatories

(*top*) 1937 Sept. 10. Exposure 20^m Max. brightness
(*centre*) 1938 Nov. 24. Exposure 45^m. Faint
(*bottom*) 1942 Jan. 19. Exposure 85^m. Too faint to observe

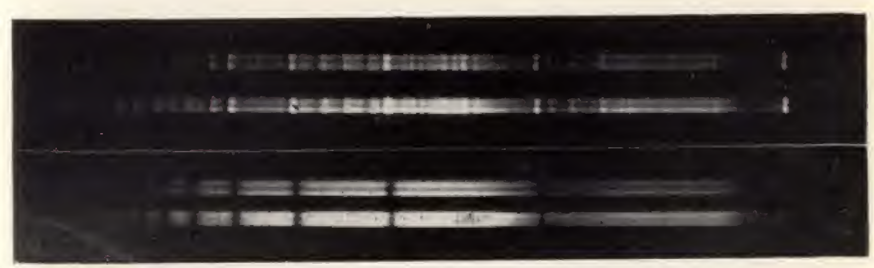


Plate 11. (*above*) Two spectra of Nova Herculis 1934 (Arcetri) 1935 January 15 (*below*) Two spectra of the blue star α Coronae Borealis, spectral class Ao, for comparison

after maximum shows a marked pause, after which the decrease of brightness continues. The spectra are similar to those of normal novae, but it is as though the whole phenomenon is on a much larger scale. A typical example of this second group is the supernova which in May 1940 appeared in the spiral galaxy NGC 4725, which is a giant galaxy, situated at a distance of 5 or 6 million light-years. At maximum the luminosity of this supernova was thirty million times that of the Sun, or one-seventh of the total brightness of the galaxy to which it belonged. After maximum the fading was for several weeks slower than that of supernovae of the first group and thereafter more rapid. The spectrum as photographed at maximum was very similar to the continuous spectrum of a high-temperature star belonging to the earliest and hottest spectral classes. As with normal novae, emission bands began to appear four or five days after maximum. They indicated a velocity of expansion of the order of about 4,000 miles/sec. The interpretation of the spectrum is clear enough. It is like the development of a normal nova though on a larger scale. Here again we encounter a division similar to that between giants and dwarfs, though the possibility of the existence of stars of intermediate magnitude between novae and supernovae cannot be excluded.

We have described one or two of the more remarkable novae and supernovae of recent times. Supernovae in the Galaxy could naturally be studied under more favourable conditions than supernovae which appear in other galaxies, but their frequency is so low, one in several centuries, that none has appeared during the 100 years since the spectroscope was introduced into astronomy, nor during the 350 years since the invention of the telescope. It appears that within historical times the 'novae' of 1054 and 1572 were supernovae.

The former appeared near the star ζ Tauri, and remained visible for several months. In this region of the sky is to be found Messier 1, known as the Crab Nebula on account of its shape, and which has a diameter of about 5′. A few years ago it was discovered that the cloud of gas which constitutes this nebula had a considerable angular motion, as though it were expanding at a constant velocity. This expansion must have started some eight or nine centuries ago, which suggests that this nebula is none other than the remnants of the supernova of 1054. Chinese and Japanese records of the position and brightness of this star, which equalled Venus and was even visible in broad daylight, support this conclusion. The spectrum tells us that the nebula is expanding at a velocity of about 800 miles/sec. Its distance from the Earth is about 5,000 light-years, and hence at

maximum this supernova, probably a member of the first group, must have attained a brightness equal to 300 million times that of the Sun. At the centre of the nebula two faint stars can now be seen. The proper motion of one of them shows clearly that it is unconnected with the nebula, but the other is a blue star of apparent magnitude 16·6 and the spectral characteristics are those of a white dwarf. In all probability this is the supernova and it is now 400 million times fainter than it was at its maximum in 1054.

The other historical supernova was the famous 'Tycho's star', so called because it was observed continuously by Tycho Brahe as long as it was visible to the naked eye. Among many faint stars near the position given by Brahe, none with unusual characteristics has yet been found which might be identified with this supernova.

A number of various hypotheses and theories have been conceived and propounded to explain the nova phenomenon, namely the explosion of a star which, before the cataclysm overwhelmed it, appeared to possess no unusual features. The theories based on the collision of two stars, or on the passage of a star through a region of condensed cosmic matter, such as a nebula, have been supplanted by other theories which, nowadays, appear to be more acceptable, and which are based on the assumption of the unstable equilibrium of certain stellar masses. Recent investigations of the internal constitution of the stars, and of their variety as far as masses, density and other characteristics are concerned, have thrown some light on this subject. We can indeed observe examples of stellar instability, though on a smaller scale than that exhibited by novae, in variable stars. As has already been said, it is highly probable that the variations of brightness of these are the result of internal upheavals which gradually come to the surface.

The relation that exists between the luminosity and the mass of a star shows that the majority of stars lie close to a mean curve. These stars may be regarded as 'normal' and as having a stable structure. Exceptions to this are the white dwarfs and certain planetary nebulae. It may be supposed that novae derive from stable conditions when, for some reason associated with the rearrangement of the mass of the star, following the transmutation of their elements, the state of equilibrium is disturbed. Alternatively they may derive from stars of unstable conditions having an exceptional internal constitution, which, at a given moment, through the nova outburst, achieve a more stable configuration.

Because we know so little of the life history of novae, both before and after explosion, it is too early to evolve a theory capable of explaining all aspects of this complex phenomenon. It may nevertheless be accepted as a provisional hypothesis until more observational data are available, that the white dwarfs, which have such great densities, represent a final state of the collapse of a normal star. If, on the other hand, the final condition of a nova is not that of a white dwarf, then it must be assumed that some stars become explosive starting from a normal structure, with a sudden breakdown of their equilibrium which carries them into conditions of instability. They cannot remain indefinitely in these conditions, but will be transformed partially or wholly into nebulae as a result of further explosions which may be cyclic, as in the case of the variables. The analogies between the light and spectra variations of novae and of certain types of variable stars, such as those of the SS Cygni or U Geminorum types, increase the plausibility of this hypothesis, so much so, that certain long-period variables such as RS Ophiuchi and T Pyxidis may be regarded either as novae or as variables.

Variables, of which SS Cygni is the type star, remain at the minimum with a fairly constant brightness for intervals of time ranging from 20 to about 150 days. At the end of each of these intervals, which are more or less regular, they rise, often very rapidly, to a brief maximum of variable duration, and then fade more slowly to their original brightness. The form of the light-curve is very characteristic, but the group, which also contains other varieties, consists of faint stars, so that up to the present time our knowledge of their spectra and colours is rather scanty. All these variables, including novae and supernovae, may be called 'cataclysmic' to distinguish them from other types of variables including Cepheids. Although the latter exhibit a similar phenomenon of disturbed equilibrium, this is on a smaller scale and, as we have seen, probably involves only the outermost layers of the star. In both cases a series of oscillations is set up which will tend gradually to be damped down and die out.

From the relations existing between the amplitudes of the light-curve of the cataclysmic variables, it appears that novae have a period of the order of 100,000 years. This is a short interval in the life history of a star, but too long to be checked by our observations. In this case, as in other phenomena presented by the universe, such as the stability and instability of the stars, their variation of brightness and their evolutionary stage, we are concerned with a question

of scale. Nevertheless it must be accepted that a nova is the overwhelming explosion of the whole of the material forming a star, only a part of which is subsequently returned to the star, the greater part being converted into a nebula which remains within its gravitational field or which is dispersed into space.

During the two centuries up to 1950, about one hundred novae had been discovered in the Galaxy. These discoveries may be described as accidental. It was clear that a systematic investigation would be necessary in order to establish the frequency of their occurrence and their distribution in space. Such a systematic survey has already been in progress for some years with the Schmidt telescopes at Mt. Palomar. Selected areas in Scorpio, Sagittarius, Aquila and Cygnus, where novae had appeared most frequently in the past, have been studied carefully.

Three novae in Scorpio were discovered at Mt. Palomar and at the Tonantzintla Observatory in Mexico during 1950. The first of these increased from magnitude 18·5 to magnitude 9 in about 10 days, afterwards fading slowly to magnitude 15. The second seemed to be a slow nova, which brightened from magnitude 18 to magnitude 8. The third, on the other hand, rose from magnitude 18 to magnitude 11 in a few days. Their spectra were also photographed, and revealed radial velocities of the same order as those encountered among other novae. The continuation of these investigations will provide us with more detailed knowledge of the regions of the sky for which novae and supernovae show a preference, and of the frequency with which they appear.

It seems likely that novae are emitters of radio waves, which, following the rapid development of the technique of radioastronomy, we are now able to receive from various regions of the sky. One of these radio sources coincides exactly with the position of the Crab Nebula, which, as we have seen, is believed to be the remnants of the extremely brilliant supernova that appeared in 1054. There is little doubt that radioastronomy will be able to provide new and important data concerning novae.

The examination of the extraordinary developments to which the spectra of novae are subject (Plate 11) also reveals something of the progressive variations of the gases that are emitted during the course of the outburst. During the first phase of the explosion of Nova Herculis 1934, for example, the atoms of FeII and CaII were detected, as well as the forbidden lines of neutral oxygen. Later, the lines of HeI and HeII, and the forbidden lines of OIII appeared, and

the hydrogen lines, which were at first predominant, then slowly faded. In the spectrum of Nova Aquilae, the lines of NII were followed by those of NIV and in that of Nova Pictoris the lines of FeI gave way to the forbidden lines of FeVII.

This continuous increase in the degree of excitation in the atmosphere of a nova is a characteristic feature of the development of the outburst. When the maximum is past, a progressive fading of the continuous spectrum is observed, the emission lines disappear, and after an interval of months, years or centuries, the nova returns to its pre-explosion conditions. From this it would appear that the explosion, however cataclysmic it may be, is not entirely destructive, but involves only the outer layers of the star. This is also indicated by the existence of 'recurrent' novae, such as T Coronae Borealis (1866–1946), which repeat the nova phenomenon at intervals of greater or smaller regularity. Attempts to estimate the quantities of material ejected by novae during their explosive phase suggest that only a very small proportion of the whole mass of the star is lost, perhaps only a thousandth.

FLARE STARS

Among the variable stars we can consider several stars which show very sudden and rapid increase in brightness. This can be compared to the flares which appear on the Sun. Within a few seconds the brightness of the star can increase very considerably, then it fades, at first rapidly and then a little more slowly.

This phenomenon appears in stars of various spectral classes but primarily among the dwarfs. It is in fact evident among the red dwarfs which are in the neighbourhood of the Sun (UV Ceti-type stars), as well as in the stars of the T Tauri-type, which belong to star associations enveloped by irregular nebulosities both bright and dark, and in ex-novae like the variables of the U Geminorum-type.

Rapid variations in brightness are also observed in some eclipsing binaries forming close pairs like W Ursae Majoris, and UX Ursae Majoris.

Generally speaking the great flares are very short lived. As an example we can mention the case of UV Ceti which on September 25, 1952, increased its brightness by 0·25 magnitudes within a second. The speed of this increase is 500 times that of Nova Aquilae 1918 in its rise to the maximum.

UV Ceti variables are all red dwarfs. They generally belong to the spectral classes from M3 to M6 and have absolute magnitudes of the order of +13. These stars have an emission spectrum in which the hydrogen lines of the Balmer series and the CaII lines can be seen.

T Tauri variables which show this 'flare' effect are very common in the nebula in Taurus, in the Orion Nebula and in NGC 2264.

Flares of very small amplitude, lasting a few minutes, have been detected in typical novae at their minimum, such as in Nova Cygni 1876 ($\Delta m = 0{\cdot}30$) and in Nova Aquilae 1918 ($\Delta m = 0{\cdot}26$). Rapid variations have been observed in MV Lyrae ($\Delta m = 0{\cdot}44$) which probably is an ex-nova.

CHAPTER XI

Position and Motion of the Stars — Motion of the Sun in Space

The stars occupy well-determined positions on the celestial sphere enabling us to recognize the same outlines which in ancient times suggested to man the division into constellations. Although at first glance the stars visible to the naked eye may appear countless, in actual fact the total number visible in both hemispheres is only five or six thousand. As Galileo quickly discovered when he started to use the telescope for astronomical observations, this number increases very rapidly when a telescope is used. A 2·5-inch objective will show 320,000 stars and a 39-inch objective will show one hundred million, while the great Mt. Wilson and Mt. Palomar reflectors can photograph several thousand millions.

The solution of many astronomical problems soon made essential the determination of the positions, first of the brightest stars, and then of progressively fainter ones. Among the earliest of these problems were the determination of the motion of the Earth and planets around the Sun, and the linking of the planets and the stars by a single system of co-ordinates. Although the stars may provide reference points, which their great distances from the Earth permit us to regard as fixed, it is nevertheless extremely difficult to establish a fixed common origin of reference in space to which all the stars may be referred. For this reason the most commonly used system of co-ordinates for defining the position of the stars in the sky is that of equatorial co-ordinates (right ascension and declination) which has for poles those of the Earth and for fundamental plane that containing the equator on which the right ascension is measured starting from the point of the Vernal Equinox. Because the planes specified in this way vary with time, owing to the phenomena of 'precession'

and 'nutation', the co-ordinates of the stars are also continuously changing, and must therefore be reduced to some stated epoch before valid comparisons can be made between them.

In order to avoid terrestrial references, other fundamental planes must be employed, such as that of the Milky Way, which is known as the galactic plane. The position of a star can be defined with reference to the galactic plane by means of galactic latitude and galactic longitude. The galactic latitude of a celestial object is its angular distance north or south of the galactic plane. The galactic longitude is measured along the galactic plane taking as origin the point where the galactic plane intersects the celestial equator. The galactic co-ordinates of the stars are thus completely independent of the motion of the Earth. It is still usual, however, to specify stellar positions by means of equatorial co-ordinates, and great numbers of these are listed in various visual and photographic catalogues. Associated with these are star charts which are useful for purposes of orientation or, when they are made photographically, for determining the positions of stars which are too faint to be observed visually, but are within the limit of light grasp of various modern instruments. Photographic charts are also extremely useful for the study of variables and the discovery of novae. In order to obtain a complete record of the heavens, the Harvard Observatory at Cambridge in the United States, together with its stations in the southern hemisphere, has undertaken a systematic photographic survey of the whole celestial sphere at regular intervals and with instruments having a wide field.

In 1949 the Mt. Palomar Observatory, under the auspices of the American Geographical Society, started the compilation of a photographic atlas by taking photographs of the northern celestial hemisphere and part of the southern with the 48-inch Schmidt telescope. The *Sky Atlas* consists of copies of the original negatives each measuring 14 by 14 inches and covering a field of 7°. The photographs were taken in blue and red light and reach down to magnitude 20·3 for the blue light, this being the photographic limit of the instrument.

Before the introduction of photography, the only instruments capable of determining the positions of stars with sufficient accuracy were the mural quadrant, and later the meridian circles. The latter is a telescope which can rotate about a horizontal axis orientated east and west, so that its movement is restricted to the plane of the meridian. Sun and stars can thus be observed only at the moment of

their transit across the meridian of the place of observation, and, given the stability of the instrument, the position of the Sun can be directly related to the position of the stars preceding and following its meridian passage. By means of successive observations of a limited number of the brightest stars, it was possible to refer the co-ordinates of these directly to the fundamental planes of the celestial sphere. To such 'absolute' right ascensions and declinations, the 'relative' co-ordinates of a much greater number of stars could then be referred.

In this way a number of fundamental catalogues were compiled, the most recent and the one most generally used contains the positions of 905 stars, for the epochs 1925 and 1950. This catalogue, known by the abbreviation *FK*3, is nowadays the basis of the ephemerides published annually by the larger national observatories for the use of astronomers and navigators. Other fundamental catalogues, together with many additional ones related to them, compiled either by individual observatories or by the joint effort of several observatories in different parts of the world, were gradually published. One of these is the *Astronomische Gesellschaft* catalogue, so called because it was initiated by the German Astronomical Society, It was compiled from observations made at twenty different observatories, to each of which, according to its geographical position, was assigned a certain area of the sky. It consists of twenty-five catalogues, all reduced to the same system, in which are given the positions of all stars down to about magnitude 9, for the epoch 1875.

With the introduction of photography, and the development of photographic objectives capable of covering a field of several square degrees, the determination of stellar positions became both less laborious and more speedy. Without in any way replacing the visual method with the meridian circle, differential measurements of plates obtained with various times of exposure, allowed the positions of large numbers of stars to be determined relative to fundamental stars or to others of well-determined positions, by means of rectilinear co-ordinates. These could then be easily converted to equatorial co-ordinates. In 1887 a programme was organized whereby eighteen observatories in all parts of the world co-operated to produce the *Astrographic Catalogue* and the *Carte du Ciel*. Each observatory used an identical instrument, a photographic refractor of 13-inch aperture and a focal length of about 11 feet. The plates, measuring 6·3 × 6·3 inches, cover an area of the sky of about 2° × 2° on a scale of about

0·8 of an inch per 10 minutes of arc. Two plates were obtained for each area, one with an exposure of 5 minutes in order to obtain stars down to magnitude 11, which is the limit of the catalogue, and another of 30 minutes, to obtain stars of magnitude 14, which is the limit of the *Carte du Ciel*. The image of a rectilinear grid of fine lines was also recorded on each plate, and by means of this, the co-ordinates of the stars, referred to the centre of the plate, can be determined.

The positions are determined with a plate measuring machine, capable of measuring differences of position of the order of 1μ. Long and patient work has resulted in the determination of the positions of 2 million stars on 45,000 plates, and in the linking of these to fundamental stars the co-ordinates of which have been determined either by meridian circle observations or from already existing catalogues. Work on the catalogue is almost complete, and some observatories, such as those of Catania and of Helsingfors, have also computed the equatorial co-ordinates. The *Carte du Ciel* covers only about 40% of the whole celestial sphere, in a nearly continuous band extending on either side of the celestial equator between declinations $+39°$ and $-17°$.

So vast an undertaking, extending over more than half a century, not only provides the accurate positions, numbers and distribution of the stars at the time of observation, but also has the very important result of revealing their proper motions when these positions are compared with those obtained by measurements made with an adequate lapse of time between them. All the stars are in fact in motion through space, and if they appear 'fixed' to us it is only because their very great distances reduce their angular displacements on the celestial sphere to such small quantities which can only be detected by accurate measurements by means of a telescope. The component of the motion of a star along the line of sight can be detected only with the spectroscope because the distance of the star is so great that the change in brightness of the star due to its approach or recession from the Earth is too small to be observable. The greater part of the difference between the positions of a star as given in different catalogues is due to apparent movements, shared by all the stars in a given region of the celestial sphere. In addition to precession and to nutation these are due to 'aberration' and to 'parallax'. Aberration is a combined effect of the velocity of light and that of the Earth in its orbit, and parallax is the apparent displacement of the star, due to the Earth's motion around the Sun, the size of which

is inversely proportional to the distance of the star. What remains, apart from systematic errors which are determined with great care, is the star's own 'proper motion' as seen from the Sun, and therefore affected by whatever motion the Sun itself may have towards some definite point in space.

These apparent angular proper motions are in general extremely small, amounting to a fraction of a second of arc per year, and they are naturally smaller for distant stars than for those relatively near to the solar system. In very few cases are they larger than 1″. Barnard's star, of 9·7 magnitude and of class M5, has an exceptionally large proper motion amounting to 10″·25 per annum. This star is also the nearest neighbour of the solar system if we exclude the stars in Centauri.

The most extensive collection of proper motions is to be found in the General Catalogue compiled by Boss at the Dudley Observatory at Albany (U.S.A.). This catalogue gives the positions of 33,342 stars reduced to the epoch 1950 and their proper motions are deduced from 238 catalogues going back as far as 1755. Hence the position and proper motion of these stars, which include those brighter than magnitude 7 and many fainter ones of special interest, may be accepted as being accurate.

To facilitate the detection of stars with large proper motion, an instrument has been devised which allows the comparison of photographs of the same region of the sky taken at a suitable interval of time of one or more years. As seen through the eyepiece of the 'blink-comparator', as this instrument is called, the two photographs are superimposed, and then viewed in rapidly alternating succession. If a star has the same position on the two plates its image will remain motionless in the field of view, but if a star has moved during the interval elapsed between the exposure of the two plates, its image will appear to jump back and forth, thus revealing its proper motion during this interval.

If the distance of a star of known proper motion has not been determined, nothing can be said about its true motion in space. On the other hand if its spectrum can be photographed, and the Doppler displacements of the lines can be measured, then its linear motion along the line of sight, expressed in miles/seconds, can at once be derived. The radial velocity, like the proper motion, must be related to the Sun and therefore has to be freed from the effect of both the diurnal rotation of the Earth and its revolution round the Sun. The displacements of the spectral lines in the spectrum of the star are

measured by comparing the stellar spectrum with that of a terrestrial source. From the displacement $\Delta\lambda$ of a given line of wavelength λ, the radial velocity v of the star is at once obtained from the expression:

$$v = \pm c\Delta\lambda/\lambda$$

where c is the velocity of light. The velocity is said to be positive when the wavelength increases, that is when the star is receding from the Earth, and negative when the star is approaching.

Much effort has been devoted to technical improvements that may make these important measurements increasingly accurate. The image of the star whose spectrum is to be examined is focused on the slit of the spectrograph mounted at the end of the telescope, and it is maintained accurately in this position. The spectrum of a terrestrial source, whose image is also focused on the slit, is recorded on the photographic plate close to that of the star. According to the spectroscopic class of the star, this laboratory source may be a discharge tube containing hydrogen or some other gas, or an arc or spark of iron or of some other metal. Iron is most frequently used owing to the great number of lines in its spectrum, and because the wavelengths of many of these lines have been accurately determined and may therefore be used as standard lines.

In this way the radial velocities of ever fainter stars have been measured, primarily at Lick Observatory on Mt. Hamilton, California, which has issued an extensive catalogue. Owing to the difficulty of observing the fainter stars, the radial velocities determined up to the present time are limited to about 8,000 stars brighter than magnitude 7 or 8, although more powerful instruments could extend this to stars of 12th magnitude. The velocities, on average, lie between ± 12 miles/sec.; values exceeding about 60 miles/sec. are rather rare. The precision of the measurements depends upon the dispersion of the spectrograph. This can be increased, when the star is bright enough to provide the instrument with sufficient light, by employing two or three prisms, or else a diffraction grating. In the case of the fainter stars we must be satisfied with a smaller dispersion and therefore reduced accuracy. The accuracy also depends upon the spectral class since spectra of some classes show more sharply defined lines than those of other classes. Where the spectrum has numerous lines, and sufficient dispersion can be used, the radial velocity can be determined with an average error of about 0·3 miles/sec., increasing to about 5 miles/sec. in less favourable circumstances.

The objective prism has also been used to determine the radial velocity of groups of stars. This instrumental arrangement consists of a circular prism mounted in front of the objective glass of a refractor, or in front of the mirror of a reflector, to form a slitless spectrograph which will give images on the photographic plate of the spectra of all the stars within the field of the telescope. Since such a photograph lacks a comparison spectrum, it is necessary to use a filter—a neodymium chloride filter for example. The radial velocity is then derived by measuring the separation of the stellar lines and the neodymium absorption bands. This method is incapable of giving very accurate results, but it is nevertheless valuable on account of the speed with which it can yield the radial velocities of large numbers of stars.

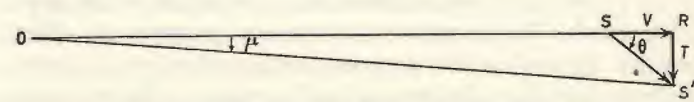


FIG. 31. Spatial velocity, radial and tangential velocity.

Once the proper motion, the radial velocity and the distance from the Sun of a star are known, it is possible to calculate its true motion in space or, as it is called, its spatial velocity, relative to the Sun.

The proper motion of a star, expressed in seconds of arc per year or per century, is represented in figure 31 by the angle μ, subtended at the Sun (O) by a displacement of the star from S to S'. The vector $SS' = V_s$ represents the spatial velocity, and may be resolved into the two components $SR = V$, the radial velocity, and $RS' = T$, the tangential velocity. In order to be able to express the latter, and hence the spatial velocity in linear units, such as miles/seconds, we must also know the distance of the star. This involves the determination of its parallax, or the angle subtended at the star by the radius of the Earth's orbit. Therefore if D represents the distance of the star from the Sun, r the radius of the Earth's orbit and p the parallax in seconds of arc, we have:

$$D = r/\sin p = 206{,}265''\ r/p$$

and knowing p, we have:

$$T = \mu \text{ miles/sec.} = 2{\cdot}94\ \mu/p$$

where the numerical coefficient is the ratio between the distance

Earth–Sun, 93,005,000 miles and 31,556,926 seconds, the length of the tropical year. The spatial velocity in miles/seconds is then given by:

$$V^2_s = V^2 + T^2$$

Large numbers of determinations of proper motions and radial velocities have shown that, although the distribution of positive and negative values is random, there exist nevertheless groups of stars which move through space with virtually identical proper motions and radial velocities. This shows that these groups must form a physically connected unit, the 'moving clusters' as they are called, such as those in Taurus, in Ursae Major and in Scorpio. The spatial motion of the Hyades cluster in Taurus appears to converge upon a definite point on the celestial sphere which indicates the parallel directions in which the stars of the cluster are moving while receding from the Earth. The apparent convergence is simply an effect of perspective. Apart from this common motion other types of systematic motions have been discovered, and for these a different explanation must be sought.

It was suspected, even before it was established, that the Sun, like all the other stars, must have a spatial velocity which could only be detected by indirect means, through the observed motions of the other stars. If the Sun and the rest of the solar system is indeed moving towards a definite point in space with a certain velocity, then the effect of perspective will give different and clearly distinguishable systematic motions to those stars towards which we are moving, as well as to those away from which we are moving, and also to those at right angles to our line of motion. We may thus speak of the probable spatial motion of the Sun relative to the general motion of the stars taken as reference, but not of its absolute motion. Thus, in the general motion of the stars, it is possible to distinguish between a systematic component due to the Sun's displacement, 'parallactic motion', and the component due to the individual motions of the stars themselves, 'peculiar motion'.

The spatial velocity of the Sun may be specified by the point on the celestial sphere, called the 'solar apex', towards which the Sun is moving and by its velocity. The assumption that the peculiar motions have no preference for one direction rather than another, namely that they are distributed at random, is only a first approximation to the truth, which we find necessary when we wish to determine the motion of the Sun. In any case, the derived motion will be a mean

value, relative to the groups of stars considered, and we have also seen that these stars will have a shared mean motion if they belong to a physically associated stream. The derived figures for the position of the apex and for the velocity of the Sun will thus have significance only if the stars to which they are referred are specified.

Given the equatorial co-ordinates (right ascension α and declination δ) of the solar apex and its linear velocity $V\odot$ we obtain the mean values which follow and which are derived from many investigations of the proper motions and radial velocities of a large number of stars chosen from among our nearer neighbours,

$$\alpha = 270^\circ = 18^h$$
$$\delta = +30^\circ$$
$$V\odot = 12 \text{ miles/sec.}$$

The point thus defined lies close to the star ξ Herculis.

If now, from the observed motions of the stars under consideration we eliminate this solar motion, we can divide the stars into groups and study these separately. If we knew all their absolute magnitudes and their spectral classes, the natural way of grouping them would be in terms of the Russell diagram. As this, however, is not possible, we shall consider the various spectral classes taking into account whether the stars are giants or dwarfs. In this way various peculiarities have been discovered, and these have led to the development of different hypotheses concerning the distribution and motion of the stars of the Galaxy. The peculiar motions of the fainter stars are more rapid than those of the brighter stars. On average, the peculiar radial velocity increases by about 7% from one absolute magnitude to the next fainter. Furthermore it has been found that the mean of the peculiar radial velocities of stars of a given spectral class is positive and not zero, as it would be if these velocities were distributed at random. This effect amounts to 3 miles/sec. for stars of class B, to approximately 1·2 miles/sec. for those of class A, and still less for the other classes. It is still not known whether this effect is due to systematic errors in the wavelengths of the lines of the comparison spectra, or to a relativistic red shift produced by differences of stellar masses, which are in fact larger in the case of stars of class B.

In addition to this, the investigation of the peculiar motions of the stars in different regions of the sky revealed certain asymmetrical effects which led the early investigators, such as Kapteyn and Schwarzschild, to formulate the hypotheses of 'two star streams' or of 'ellipsoidal' distribution of velocities. In more recent years these

hypotheses have been combined, particularly by Lindblad and Oort, into the theory that the whole system of stars surrounding the Sun, namely the Galaxy, is rotating about an axis perpendicular to its principal plane. If the system rotated as a solid body, the radial velocities of stars at different distances from the centre, as seen from any point within the system, could not be observed. If, on the other hand, it were a question of orbital revolution about a central mass, similar to that of the planets around the Sun, the velocity would decrease from the centre towards the edge. Although the effect is small in the case of the nearer stars, it has nevertheless been possible by observations to establish its existence and to confirm it by the observation of more distant objects. We shall return to the subject of galactic rotation after we have discussed the problem of the distances of the stars.

CHAPTER XII

Stellar Distances

As long ago as the early seventeenth century, Galileo had realized that the annual motion of the Earth around the Sun must be reflected by the nearest stars to the solar system. But neither then, nor for many years to come, were instruments available that were sufficiently accurate to detect the apparent sinuous motions of the nearest stars that result from the combination of their proper motion and of the 'parallactic ellipse' which is the image of the orbit described by the Earth around the Sun. The annual parallax of a star is the angle subtended by the radius of the Earth's orbit at the star and amounts to less than one second of arc in the case of even the nearest star. This annual parallax could only be measured with the aid of accurate instruments such as the heliometer and the meridian circle. Such a measurement was first made by Bessel in 1838 for the star 61 Cygni. Since that time, astronomers have increased the number of direct trigonometrical parallaxes, to the limit that could be attained by both visual and photographic methods. It was soon realized that stars near to the solar system, that is stars having a parallax larger than a few hundredths of a second of arc, were very few, and that our knowledge of the parallaxes, which is so essential to the study of the structure and constitution of the universe, would remain extremely limited unless other methods of measurement were evolved.

Fortunately it was possible to develop two indirect methods by which the parallax of a star could be derived from the determination of other quantities on which it depends. Although their use involves certain assumptions, they have, nevertheless, produced some notable results, particularly in connection with the mean parallax of classes of stars, which it is impossible to measure directly. Moreover, the increasingly accurate study of stellar spectra, and the discovery of the period-luminosity relationship shown by certain types of variables,

have made it possible to determine the absolute magnitudes of such stars from their physical characteristics. Once the absolute magnitude of a star is known, we can calculate its distance and the limit is imposed only by the luminosity of the star.

The visual method of measuring stellar parallaxes consists of measuring, with a meridian circle or a heliometer, the difference of right ascension between the star in question and that of two or more suitably selected comparison stars. With the meridian circle the time of transit of the star at the meridian is recorded automatically on a chronograph, together with time signals, when the observer follows with a micrometer the diurnal motion of the star in the field of view of the telescope. Visual methods, although they have provided valuable results, have in recent years been replaced by photographic methods. These make use of reflectors or refractors of long focal length, so as to obtain a large enough scale on the plate to enable the measurements of the very small displacements to be made.

In order to utilize the whole of the baseline provided by the Earth's orbit, the photographs must be taken at an interval of six months, when the parallactic factors will have their maximum positive and negative values. They must also be taken at the same hour angle, to ensure identical conditions of atmospheric refraction and dispersion, and care has to be taken that the brightness of the star the parallax of which is being measured is nearly equal to that of the comparison stars in the field. This is achieved by means of a diaphragm consisting of two semicircular discs which can be rotated around their common centre so as to leave an open segment of from 0° to 180°. This diaphragm is then mounted in front of the photographic plate, near to its centre where the image of the star will fall and is rotated by a small electric motor mounted near the plate holder. In this way the light from the brighter stars is reduced so as to render it equal, as much as possible, to that of the comparison stars. About a dozen photographs are obtained, and on each of these the difference between the co-ordinates of the star and those of five or six nearby stars is measured. From these the most probable values of its parallax and proper motion can be derived by the method of least squares, bearing in mind that its proper motion will of course be superimposed on its parallactic displacement.

It will thus be seen that what is obtained is the parallax of the star relative to the comparison stars, which are assumed to be so much more distant that their own parallax is negligible. Stars for parallax determinations were selected at first from among the

brightest stars, which in general are also the nearest, then from stars with exceptionally large proper motion, like 61 Cygni, which, again, may be expected to be relatively near to the solar system, and finally from various other categories. Reference stars are faint, and have very small proper motion. Even for these stars it is possible to derive the mean parallax by indirect methods, and this can be subtracted from the measured relative parallax, reducing it to an absolute parallax.

The mean error of trigonometrical parallaxes averages $\pm 0''\cdot 01$, and hence it is not possible to use these methods for the determination of the distances of stars more remote than 100 parsecs, or 326 light-years (one light-year being equal to 63,310 A.U.).

It can thus be seen how severely our attack on the problem of stellar distances would have been restricted if other methods had not been found. Nevertheless, the determination of the parallax of the brighter stars has in recent years been completed, wholly by the photographic method, and by international co-operation. That of faint stars with large proper motion, both in the northern and southern hemispheres, is now in progress.

The simplest assumption that is available for the indirect determination of the parallax of visible stars is that the parallax is a function of their apparent magnitude and their proper motion. It is then possible, by a suitable combination of these data, to derive a relation involving these values which have been directly determined. This method was initiated about sixty years ago by Gylden and Kapteyn, who derived empirical expressions from which an indication of the distances of the stars in question could be obtained. With the accumulation of observational data, and especially as it became possible to calculate the spatial velocities, the radial velocity and the motion of the solar system, other more accurate methods have also been evolved.

One example of such methods was that developed by Campbell, of the Lick Observatory, who was one of the first observers to determine the radial velocities of a large number of stars. These radial velocities, freed from the parallactic motion of the solar system, can be combined with the components τ''_m of the proper motion at right angles to the great circles passing through the star and the solar apex. Assuming that the mean of the radial velocities V_m is equal to the corresponding mean of the linear components of the proper motion, Campbell determined the mean parallax p''_m.

$$p''_m = 2\cdot 94\, \tau''_m / V_m$$

When he arranged his results according to the spectral classes of the stars concerned, Campbell found that stars of Father Secchi's class II, that is stars of the type of the Sun, appeared to be nearer to us, with a mean distance of 150 light-years. The distances of class I stars are much greater, reaching 500 light-years.

In the course of an investigation of precession and of the motion of the Sun based on a large number of stars, Boss succeeded in determining the mean motions τ in a direction at right angles to the parallactic motion of the Sun, for various types of stars. He started from the assumption that, apart from the apparent parallactic displacement due to the motion of the Sun, the proper motions of stars, or of systems of stars having a common motion, are distributed at random and show no preference for one direction rather than another. He confirmed that radial velocity is a function of spectral type, but that the mean distance of the majority of stars of class I and of all those of class II are the same, namely about 326 light-years. In the case of stars of classes earlier than class I (Draper's classes O and B) he confirmed the greater distance found by Campbell.

More recently Seares, at Mt. Wilson Observatory, obtained the mean parallaxes of stars in all parts of the sky for each successive apparent magnitude from 1 to 13, irrespective of spectral classes. The mean parallaxes are:

Magnitude	Mean parallax
1	0″·083
5	0″·018
9	0″·004
13	0″·001

Thus for a magnitude difference of 12 the distances increase from 40 to 3,260 light-years.

These mean parallaxes are smaller in the plane of the Galaxy than in the vicinity of its poles. Observations made in the Galaxy only reach distances which are too small in relation to its whole dimension, but other indirect methods have been devised to enlarge the scope of our investigations of the Galaxy and beyond.

Another indirect method, which however is limited by the possibility of separating visually the components of double stars, yields what are known as 'dynamic parallaxes', so called because they rely on the application of Kepler's third law. We have already quoted the formula which gives the sum of the masses of the two components of a binary system. From this the parallax p is given by:

$$p'' = a''/\sqrt[3]{t^2(\mathfrak{M}_1+\mathfrak{M}_2)}$$

If it is assumed, as a first approximation, that in a binary system for which the orbit, and therefore a'' and t, have been determined, the sum $\mathfrak{M}_1+\mathfrak{M}_2$ is equal to twice the mass of the Sun, then the approximate value of p'' can be calculated. Knowing this, the absolute magnitudes of the two components can be derived from their apparent magnitudes, and their masses can be obtained from the curve of the mass-luminosity relation. Adding together these values of the masses, the calculation of the parallax by means of the above expression can be repeated, successive approximations finally yielding a value of p'' which no longer changes. It has been established that the deviations of individual stars from the mass-luminosity curve are generally small, and hence this method gives reasonably accurate results. It has also been extended to double stars having very slow motion and for which, therefore, the period cannot be accurately determined. The velocity of the relative motion of the components can be substituted for this period. The velocity can be obtained by micrometric measurements of the two components, and these measurements are repeated throughout the year.

In this way it has been possible to measure the dynamic parallax of about 1,500 binaries. The dynamic parallaxes are considerably greater than the mean values obtained for single stars of the same magnitude. This is understandable when it is remembered that the possibility of resolving a double star depends upon the resolving power of the telescope, and that even with the largest telescopes the double stars which can be resolved are relatively close neighbours of the solar system.

With the discovery of the Cepheids' period-luminosity relationship, the astronomer has more powerful means of sounding space. The usefulness of this method is limited only by the possibility of seeing these variables and measuring their periods. Once these are known, the absolute magnitude of the star can be obtained from the curve, and when this is compared with the apparent magnitude, allowance being made for interstellar absorption, the parallax can be immediately derived. The distances of Cepheids, situated within the galactic system, can in this way be determined with very satisfactory accuracy. More than this, Cepheids have also been detected in extragalactic space, in star clusters and in star clouds, thus allowing the distances of these objects to be determined and greatly increasing

the scope of our explorations of the universe. Two shortcomings of this method spring from the fact that it is uncertain whether the Cepheids belong to population I or II, and by the fact that the absorption exercised by interstellar matter varies from one region of the sky to another.

Finally, when atomic theory provided an explanation of the origin and appearance of different spectral lines, a method was developed which in many cases allowed the absolute magnitude of a star to be deduced from a simple examination of its spectrum. Adams and Kohlschütter, of Mt. Wilson Observatory, compared the spectra of giants and dwarfs belonging to the same spectral class. They found that the spectra of both these types of stars appeared identical since both have the same surface temperature. Nevertheless a more careful examination revealed among certain lines differences of intensity which were a function of the absolute magnitude of the stars under consideration.

Let us consider, for example, the two stars 61 Cygni and α Tauri (Aldebaran). They are both of class K5, and their parallaxes, reliably determined by the trigonometrical method, are respectively $0''\cdot30$ and $0''\cdot06$. Since their apparent magnitudes are respectively 5·6 and 1·1, their absolute magnitudes can be calculated as 8·0 and —0·1. In reality, therefore, α Tauri is nearly 1,700 times more luminous than 61 Cygni, although it appears to be only 60 times brighter. Even a casual examination of their spectra will show that among the many lines in the two spectra, the intensities of some of the lines are different. For example, the arc line of neutral calcium at λ 4455 Å is intense in the spectrum of 61 Cygni but weak in that of α Tauri, while the spark line of ionized strontium at λ 4216 Å is very intense in α Tauri and less so in 61 Cygni. Other pairs of lines exhibit the same phenomenon. It may be concluded that the low excitation arc lines are predominant in the spectrum of 61 Cygni, whereas the high excitation spark lines, the 'enhanced' lines, are predominant in that of α Tauri.

A somewhat analogous phenomenon is observed in the spectra of sunspots when they are compared with the spectrum of the chromosphere. We know that in the sunspots the temperature is lower than that of the photosphere and that the density is considerably higher than that of the chromosphere. If the general characteristics of the spectra of the two stars under consideration are the same, as well as the energy distribution of the continuous spectrum, the detailed differences between them cannot be the result of temperature dif-

ferences, and we are therefore forced to assume that the densities of their absorbing layers are very different.

The brightness of α Tauri shows it to be a giant while 61 Cygni is a dwarf. The volume of α Tauri must therefore be many times greater than that of 61 Cygni, and its outer layers, which produce the spectrum, must be correspondingly less dense than those of the dwarf. Herein lies the cause of the observed spectral differences.

The earliest investigations along these lines were not undertaken with the intention of making systematic determinations of stellar distances. It was simply hoped to evolve a quick method of recognizing stars of low intrinsic luminosity, which might be expected to be near to the solar system and therefore have parallaxes measurable by the trigonometrical method. Observations, however, made primarily at Mt. Wilson, of large numbers of spectra of stars mostly of class II in which the distinction between giants and dwarfs is well marked, and whose parallaxes had been determined by other methods, allowed curves to be drawn representing the changes in the ratio of intensity of pairs of lines as a function of absolute magnitude.

These curves permitted the determination of the absolute magnitudes, and therefore of the distance of stars of unknown parallax, simply by the examination of the relative intensity of suitably chosen lines in their spectra. At first, this method was only applied to stars of classes F to M, but later it was extended, though with certain limitations, to other types. In the case of classes B and A, in which the distinction between giants and dwarfs is not sharply defined, certain characteristics of the lines, particularly the presence and intensity of the lines as a function of spectral type, give a sufficiently close value of the absolute magnitude.

This method of determining what is known as the 'spectroscopic parallax' is limited only by the possibility of photographing the spectrum of the star. As regards accuracy, if calibration curves based on the values of trigonometrical or group parallax obtained by independent methods are reliable, the mean error in the determination of the absolute magnitude amounts to $\pm 0^{m}\cdot 5$, corresponding to a mean error in the parallax of $\pm 20\%$. The mean error of modern trigonometrical parallaxes is $\pm 0''\cdot 01$, and therefore if the parallax exceeds $0''\cdot 05$, the trigonometrical method is superior to the spectroscopic. Since the majority of the stars have parallaxes much smaller than this, which therefore are not measurable by the trigonometrical method, the importance of this new method will be appreciated.

The most extensive series of determinations made by the spectroscopic method, involving over 4,000 stars of spectral classes from A to M, was that of Adams and his colleagues at Mt. Wilson. The pairs of lines chosen were among those of iron, calcium, titanium and strontium, neutral and ionized and the total intensities, rather than the widths or depths of the lines, were determined empirically. While the intensity of the lines of ionized atoms increases with increasing absolute magnitude, those of neutral atoms usually decrease in intensity. For comparison purposes, lines were chosen having an intensity which varies little or not at all with absolute magnitude. Among giants of classes K and M certain metallic lines are extremely sensitive to changes of absolute magnitude, and therefore constitute valuable criteria for its determination.

It had been noticed for some time that, contrary to the general case, the spectral lines in the spectra of some stars were exceptionally intense and sharply defined. Later work has shown that such stars, which have very small proper motions, must be even more luminous than the average giant, and they were accordingly named 'supergiants'. These stars are visible even when found at very great distances from the solar system. In the spectra of supergiants, the enhanced lines of the metals, particularly iron and titanium, are much more intense, and the arc lines weaker. The lines of hydrogen are more intense in the redder stars, and those of helium, which normally disappear in class B9, are to be seen in α Cygni, which belongs to class A2, and which is one of these supergiants.

These phenomena which enable the determination of the absolute magnitude of stars can be explained by Saha's theory of ionization, according to which the proportion of ionized atoms in a gaseous mass depends not only on the temperature but also on the pressure.

The formula already given (see p. 68) shows that, for a given decrease in the pressure, P, the degree of ionization, represented by the first term in the equation, will increase in the same proportion for all the elements; while a reduction of the temperature, T, will result in a decrease of ionization which depends upon the value of the ionization potential, I. Hence the elements with low ionization potential, which are most easily ionized, are the ones that will be most ionized in the low density outer atmosphere of a giant. Those with higher ionization potential will be less ionized, while elements of intermediate ionization potential will not be greatly affected. Thus, for example, the lines of neutral calcium and strontium, which are elements with relatively low ionization potential, 6·1 and 5·7 eV

respectively, are intense in the spectra of dwarfs and relatively weak in those of giants, while the opposite is true of enhanced lines due to ionized atoms.

A refinement of the method of determining spectroscopic parallaxes is being achieved by replacing the empirical determination of the intensity of the lines with the accurate measurement of their profiles and equivalent widths obtained by means of the microphotometer. In this way it is possible to determine the number of atoms responsible for the production of the various lines, and hence obtain a more accurate evaluation of the physical characteristics of giants and dwarfs, and of their absolute magnitudes.

As a result it will be possible to establish the characteristics and the behaviour of the two stellar populations and to extend and improve the Russell diagram.

CHAPTER XIII

The Brightest and the Nearest Stars

It may be asked whether the brightest stars are also the nearest. Some are in fact to be counted among our nearer neighbours, but apparent magnitude is, in general, an untrustworthy indication of distance. A better criterion is proper motion, since the stars differ less widely among themselves as regards velocity than as regards intrinsic luminosity. Thus, mean annual motions of 2 seconds of arc correspond to a mean parallax of $0''\cdot4$, and motions of $0''\cdot024$ correspond to a parallax of $0''\cdot009$.

Individual proper names have been given to the brightest stars which belong to all spectral classes from B to M and which are found in the northern and southern celestial hemispheres. For example Rigel (β Orionis) and Spica (α Virginis) are blue, Capella (α Aurigae) is yellow, Arcturus (α Bootis) is orange, and Betelgeuse (α Orionis) and Antares (α Scorpii) are red. Twenty-two stars are brighter than apparent magnitude 1·6, ranging from $-1^{m}\cdot6$ for Sirius, the brightest star in the sky, to $1^{m}\cdot6$ for Castor. The parallaxes of the nearer stars are known more accurately than those of the more remote stars. The intrinsic luminosity of each is greater than that of the Sun, Rigel being about 21,000 times brighter than the Sun and seven other stars more than 1,000 times brighter than the Sun. It will be seen from figure 32 that even among the small number of stars plotted on this diagram, the distinction between supergiants, giants and dwarfs is already apparent. One of the smallest dwarfs is the faint third component of α Centauri (p. 117), the triple system in the southern celestial hemisphere; this component, Proxima Centauri, has an apparent magnitude of 11, it belongs to class M, and has an absolute magnitude of 15·4, therefore its intrinsic luminosity is 0·00007 times that of the Sun. Rigel, with a parallax $p = 0''\cdot006$, equivalent to a linear distance of 540 light-years, is, on the other

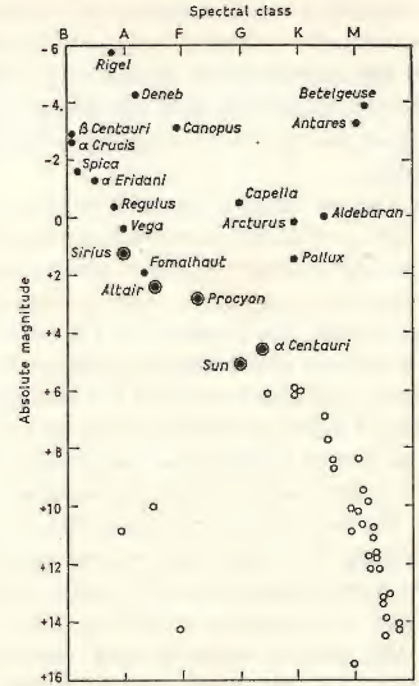


FIG. 32. The brightest and the nearest stars.

hand, a supergiant, a rare class of object in the volume of space within 500 to 600 light-years of the Sun.

Because of their enormous volume the two M-type stars Betelgeuse and Antares show measurable diameters, despite the fact that they are among the most distant here considered. Sirius, Altair, Procyon and α Centauri, on the other hand, are conspicuous in the sky because they are relatively near to us, their distances ranging from 4 light-years (α Centauri), to 16 light-years (Altair). The other stars are much fainter, having a small apparent and a small absolute magnitude.

The nearest faint stars so far discovered are, for the most part, only visible with the aid of a telescope, and are known by the name of the catalogue which first recorded their position, and their number in it. Luminosity decreases along the main sequence as far as the faintest stars of class M0. The number of such stars certainly exceeds those already discovered, since there must be many with large proper motion the parallaxes of which have not yet been determined. In the lower left-hand region of the diagram (fig. 32) are to be seen other

stars, the white dwarfs, to which reference has already been made. We do not know as yet their real frequency in space, although it appears that they are as common as the luminous stars of classes F or G, and much more numerous than the B-type stars or the red giants. Two of them are the faint companions in binary systems: Sirius and o^2 Eridani.

At the present time we know of about fifty stars with parallaxes larger than 0″·2, that is with distances smaller than 16·3 light-years. This represents one star in every volume of space equal to 373 cubic light-years. Of these, five are nearer than 10 light-years and two nearer than 6 light-years. The faintest star known is Wolf 359, so called after the astronomer who detected it owing to its exceptionally large proper motion. This star is of class M8 and apparent magnitude 13·5, and being 8 light-years distant from the Earth its absolute magnitude must be 16·6 or 50,000 times less luminous than the Sun.

Thirteen of these fifty nearest stars are members of double or multiple systems. We have already discussed Sirius, α Centauri and Krüger 60, and among the single stars we may mention Barnard's star, discovered by that astronomer in 1916, which, having a distance of only 6 light-years is our nearest neighbour after α Centauri. Its spectral type is M5, and its apparent and absolute magnitudes respectively 9·7 and 13·4, its annual proper motion is the largest known at the present time and is equal to 10″·3. Within the volume of space under consideration the star with the largest space velocity relative to the Sun is Kapteyn's star, at a distance of 12·7 light-years. This is a star of class M0, of apparent magnitude 8·8 and absolute magnitude 10·8. By combining its proper motion and radial velocity it is found that its space velocity away from the solar system is 174 miles/sec. Van Maanen's star, which belongs to class F0, appears to be a white dwarf. Its distance is 13·3 light-years, its apparent magnitude 12·3 and its absolute magnitude is 14·3. Its linear dimensions are one hundredth those of the Sun, so that it is comparable with the Earth in size, though its density is very great.

It has been calculated that the total mass of the stars distributed throughout the space occupied by these nearest neighbours of the Sun is about 20 times the mass of the Sun, and that these stars are for the most part of low intrinsic brightness and of advanced spectroscopic types. It must not be supposed that this volume of space contains only the stars mentioned here. They are probably accompanied by planets which are invisible to us, just as the planets of the solar system are invisible from the stars; and there will be other bodies

which are invisible simply because their surfaces do not emit enough light for them to be observed. Finally, the spectroscope has proved that a great quantity of cosmic matter is scattered throughout space, and therefore, some of it will also be found in the neighbourhood of the solar system.

CHAPTER XIV

The Number and Distribution of the Stars

It is a relatively simple matter to determine the total number of stars visible with our greatest telescopes, and also to investigate their apparent distribution, by means of counts made in different regions of the sky, either visually or, better still, photographically. The problem becomes much more complicated when we attempt to determine the total number of stars, including those stars which are invisible, either because of their faintness or because of their great distance, and also when we try to discover their real distribution throughout space as far as, or beyond, the limits now reached.

The first quantity to be determined is the distance of the various stars. As has been explained, this may be determined with a greater or smaller degree of accuracy, and always within the limitations imposed by the instruments available at the present time.

All the stars, some 5,000 in number, that are visible to the naked eye in both hemispheres, are brighter than about magnitude 6, but the largest telescopes can reach to 20 visual magnitude and 23 photographic magnitude. It is estimated that the number of stars of all spectral classes to magnitude 20 is of the order of a few thousand millions. Even with the naked eye it can be seen that their distribution on the celestial sphere is very irregular, particularly as regards galactic concentration.

The most recent star counts indicate that the number of stars per square degree increases rapidly with increasing faintness, but the ratio of the increase from one magnitude to the next decreases rapidly. Thus over the entire sky there are 0·2 stars of 7th magnitude per square degree, and 1·51 stars of 9th magnitude, the ratio being 7·6. The number of stars rises to 6,670 at magnitude 19 and to 21,600 at magnitude 21, the ratio this time being only 3·2. Counts made in successive zones of galactic latitude have shown that for every 20·8

stars of magnitude 11 at the galactic equator, there are only 4·3 at the poles, and when we extend the count to stars of magnitude 21 the numbers are 73,600 and 1,670 respectively. Hence the galactic concentration of the brighter stars is between 3 and 5 and rises to 44 in the case of the fainter stars.

Were it not for the existence of dark cosmic matter, which intercepts and absorbs the light of the stars, one would conclude from these counts that the star density in space decreases steadily with increasing distance from the solar system, and that this diminution is more rapid in the direction of the galactic poles than the equator. We know that cosmic matter is to be found everywhere throughout space, and that its distribution is also extremely irregular. In some regions it is dense, in others less so, and hence it cannot be assumed that it alone is responsible for the thinning out of the numbers of stars. This must, therefore, be a real characteristic of the Galaxy. It is estimated that the total number of stars in the Galaxy must be about one hundred thousand millions.

Furthermore, studies of the frequency of stars of various spectral classes have revealed that stars of population I occur mainly in the outer parts of the Galaxy, namely in the spiral arms, while stars of population II, and the fainter stars of the more advanced spectral classes, show a high degree of concentration in the inner parts of the Galaxy.

In order to discover the dimensions of the Galaxy, that is to say to construct a model, in which also can be shown the position of the Sun and of those nearer stars which have been used to establish its motion through space, recourse must be made to statistical methods. These are based, not only on the numbers of the stars, but also on their parallaxes, and hence their absolute magnitudes, their proper motions and their radial velocities. To obviate the necessity of surveying the whole sky, which would be an enormous and extremely laborious undertaking, Kapteyn evolved the scheme of 'selected areas', to be investigated through international co-operation.

These selected areas are 206 in number, and are distributed uniformly over the whole sky. Their investigation by different observatories is directed to the determination of all the relevant data for all the stars contained in them. This programme has already given some interesting results, obtained from the areas assigned to Mt. Wilson Observatory.

The methods of stellar statistics which have been worked out to

solve this problem are based on the determination of three functions, namely the 'density function', which expresses the total number of stars per unit volume; the 'luminosity function', which defines the number of these stars to be found between definite absolute magnitude limits; and lastly the 'velocity function', which is analogous to the last but refers to their space velocities. The problem is extremely complex, and because of the number of variable factors involved, its complete solution is not yet possible. Nevertheless, thanks to the work of many observers and the collection of ever more extensive observational data, stellar statistics have already led to a considerable increase in our understanding of at least the general picture of the shape, constitution and motion of the Galaxy.

According to recent work, the luminosity function shows that the number of the stars increases rapidly with increasing numerical absolute magnitude, that is with decreasing intrinsic luminosity. Thus it has been calculated that for every supergiant of absolute magnitude -5 there are 90 giants of absolute magnitude $-2{\cdot}5$, and in the case of the dwarfs for 200,000 of absolute magnitude $+5$, there are 600,000 of absolute magnitude $+12{\cdot}5$. Their numbers cannot, however, increase indefinitely; this is shown both by the star counts of visible stars, and also by the fact that if their numbers did increase all space would be full of stars. Although it cannot yet be stated definitely, it appears probable that the greater number of stars concentrate around absolute magnitude $+13$, below which the numbers begin to diminish.

The velocity function indicates that the distribution of the logarithms of the space velocities is satisfactorily represented by the law of errors, provided that stars with velocities exceeding 60 miles/sec., which appear to belong to a special category, are excluded. It has furthermore been established that the mean velocity of the stars increases with decreasing luminosity, doubling itself when we pass from stars of absolute magnitude 0 to those of magnitude 10. These functions being known, it is possible to derive theoretical formulae giving the mean parallax of stars of a given magnitude and proper motion. The values so derived can then be compared with those obtained by observations in order to improve the assumptions that have been made.

We are thus led to envisage the Galaxy as a vast conglomeration of stars having the form of a highly flattened ellipsoid of revolution, with a diameter which is five times its thickness. Towards its periphery the stars become progressively thinned out, without the

system having any definite limit. Located in the interior of this great star system is the solar system, which appears to be surrounded by a cloud of stars which resembles the Galaxy itself in being flattened and elongated, but which is very much smaller, and is inclined to the galactic equator at an angle of about 12°. A considerable number of class A stars belong to this 'local star cloud' as it has been called, which lies some 50,000 light-years from the centre of the Galaxy which, in turn, lies among the dense star clouds of Sagittarius.

In recent years Lindblad developed the hypothesis that the Galaxy consists of a number of sub-systems, each in rotation, with various velocities, about a common axis at right angles to the galactic plane. The Sun, the clouds of the Milky Way, and the great majority of the stars, which move in almost circular orbits, are members of the sub-system which rotates most rapidly, and which is therefore the most flattened about its central plane. The rotational velocity of other sub-systems, on the other hand, such as the high-velocity stars and the star clusters, is very small.

This theory of rotation, later developed by Oort, and others, also permits the independent calculation of the distance of the solar system from the centre of the Galaxy. If the system rotated as a solid body, then the radial velocities of its components, as determined from any given point, would not be affected by the rotation. But if it is a question of orbital revolution about a central mass, the velocity will decrease from the centre outwards, as in the solar system, instead of increasing, as in the case of a solid body. If it is assumed that all the stars move in circular orbits in the galactic plane, so that each has a linear velocity appropriate to its distance from the centre, it is possible to derive some final equations. These equations give: (1) the residual velocity of a star free from the motion of the Sun with reference to its neighbouring stars, and (2) the component in galactic longitude of the residual proper motion, similarly freed from the effect of the motion of the Sun and referred to a system of axes which is fixed in relation to the absolute rotation of the Galaxy. The residual radial velocity V is given by the expression:

$$V = dA \sin 2(l-l_o)$$

where d represents the mean distance of the star in question, l the galactic longitude of some particular star, l_o the longitude of the galactic centre and A is Oort's constant which measures the maximum effect at unit distance.

Oort first detected this effect in the radial velocities of type O and

B stars, Cepheids and planetary nebulae, and deduced that the centre of rotation must be situated in the direction of Sagittarius. The early results were confirmed by later investigations using stars more distant from the Sun, and foremost among these investigations were those of Joy, at Mt. Wilson, based on observations of Cepheids. As we have seen, these stars enable us to select a fairly certain scale of increasing distances, since these can easily be derived from the period-luminosity curve.

It must be remembered that a considerable degree of uncertainty is introduced by the effect that selective absorption in space has on the observed apparent magnitude. As a first approximation it may be assumed that the absorbing interstellar matter is distributed uniformly throughout the galactic plane in a layer having a total thickness of 1,300 light-years. The solution of the problem of the rotation of the Galaxy also supplied a method of estimating the total effect of absorption. Joy studied the radial velocities of 156 Cepheids, divided into five groups according to distances increasing from 1,400 to 6,500 light-years. He first established that the obscuring gases are not distributed uniformly in different regions of the Galaxy, and that the observations are better represented if the observed magnitudes are corrected for a uniform total absorption of 0·85 magnitudes per 3,260 light-years. He then found that the rotational velocity of the Sun in a circular orbit about the centre of the Galaxy is about 186 miles/sec., which corresponds to a revolution period of 207 million years. Figure 33 shows the residual radial velocities of the Cepheids observed in various galactic longitudes. The continuous curves represent the solution provided by Oort's theory, and it can be seen that this is in good agreement with the observations. The best value for the constant A appears to be about 3 or 4 miles/sec. for a distance of 1,000 light-years, and the direction of the galactic centre $l_o = 325°$.

By combining the results thus obtained from the radial velocities with those derived from proper motions, it was possible to make a new determination of the distance of the galactic centre. The figure of 30,000 light-years, so derived, was in good agreement with that provided by studies of the distribution of the globular clusters.

These investigations of galactic rotation also led to a new estimate of the total mass of the Galaxy, which appears to be of the order of two hundred million million times that of the Sun, and half of this is concentrated in the nucleus. The Galaxy, in which the solar system is embedded, may thus be envisaged as a great spiral galaxy

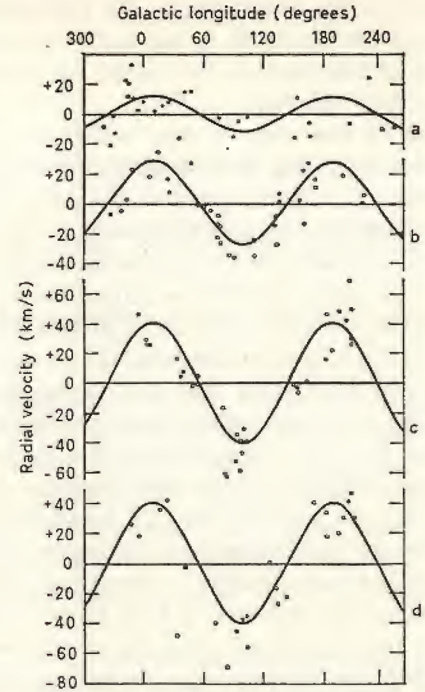


FIG. 33. Velocity curves of Cepheids. Average distance of the Cepheids: (a) 1,400 light-years; (b) 3,400 light-years; (c) 5,400 light-years; (d) 6,500 light-years. (Joy. Mt. Wilson.)

of the type of the Andromeda Nebula, in which the gravitational force exerted by its mass maintains the orbital motions of its components, and determines its shape and the distribution of its stars. The flattened central disc is for the most part composed of stars having low statistical velocities of the order of 12 miles/sec., and it includes both the Sun and the majority of the stars which we can observe. Assuming a rotational velocity of 186 miles/sec., there can be little deviation from circular motion, and it may be assumed that practically all the stars within 1,500 light-years of the central plane have circular orbits with small inclinations. As the statistical motion increases, so both the eccentricity and the inclination to the central plane will increase. This provides an explanation of the occurrence of high-velocity stars far from the galactic plane, and also of star clusters up to distances of 30,000 light-years or even more. Between the stars is scattered, irregularly, the cosmic matter the existence of

which is revealed by the spectroscope. The absorption lines of this cosmic matter are clearly visible in the spectra of the more distant stars. It is more concentrated in the central plane, where it can be observed as the 'dark nebulae'.

The stars that we can observe thus belong to a vast but finite system and we are beginning to know its constitution, its shape and its spiral structure. This spiral structure has now been revealed by exciting new developments in radioastronomy.

Radio waves are not absorbed by interstellar matter, and therefore they allow us to probe further into the galactic nucleus, beyond the thick clouds which prevent the optical radiations from reaching us. In this way, with the help of radioastronomy we can obtain a more complete picture of the Galaxy than has, so far, been possible. In the spiral arms there are large quantities of interstellar matter which consist mostly of hydrogen. Neutral hydrogen, in the normal state, does not emit any radiation in the visible domain, and in the radio domain emits only one spectral line of a wavelength of 21 cm. By studying the Doppler displacement of this line in the various parts of the Galaxy, it has been possible to detect the spiral arms of our Galaxy. Furthermore the radio waves have made it possible to determine with even greater accuracy than by optical means, the laws according to which the Galaxy rotates around a well-defined centre. These laws are more complex than they were at first thought to be.

CHAPTER XV

Star Clusters and Star Associations

Open clusters and globular clusters are families of stars more complex than double or multiple stars, and are often devoid of nebulous bright or dark cosmic matter but have, nevertheless, a characteristic structure and appearance. In these clusters isolated stars can be distinguished as well-developed objects, and therefore it is proper to consider them in this book on stars, and to reserve the question of nebulae, and of cosmic matter generally, to another volume.

As the name implies, clusters are associations or groups of many stars, but the telescope shows that the appearance of open clusters is very different from that of globular clusters. The Pleiades, for instance, form an open cluster consisting of only a few hundred stars which appear to be well separated from each other, while a few are surrounded by diffuse matter. The well-known globular cluster in Hercules is one containing tens of thousands of stars but with no intervening gaseous matter between them. The Pleiades and the Hyades are open clusters which are at distances of only a few hundred parsecs from the Sun and thus occupy a fairly extensive region of the sky. Open clusters occur near the galactic plane and for this reason are called 'galactic clusters'. About 350 open clusters and 100 globular clusters are known. One important feature of open clusters is that the constituent stars all belong to population I. Globular clusters, on the other hand, are formed entirely of stars of population II. Unlike the open clusters, they are found in all galactic latitudes and are more remote from the Sun.

According to Trumpler, the open clusters can be divided into three groups:

1. All stars of the cluster belong to the main sequence in the Russell diagram ranging from class O to class M.

2. Very few stars of the cluster are to be found in the region of the Russell diagram where giant stars are situated.

3. The majority of the bright stars in the clusters are either red or yellow giants, and the rest are to be found in the main sequence.

Variable stars, which are very numerous in globular clusters, are not found in galactic clusters. The diameters of the open clusters range from about 2 parsecs, for the smaller clusters, to 15 parsecs for the larger, but a diameter of about 3·5 parsecs is most common.

The most notable globular cluster, ω Centauri, has been known since early times, although it was then considered to be a nebulous star. Halley, in 1714, observed another notable northern cluster in Hercules but was unable to resolve it into stars. With medium-powered telescopes today, it is possible to resolve this cluster into thousands of small stars which become progressively denser near the centre and impossible to resolve. Messier, in 1771, completed his painstaking search for nebulae and clusters and compiled a catalogue of about 100 clusters, of which 27 are globular clusters, in the northern hemisphere. He was only able to resolve some of the clusters and he thought others to be devoid of stars, appearing to him to have a luminous centre the intensity of which became progressively weaker, tending to merge with the background of the sky. With modern optical means all globular clusters appear to be of similar type to that in Hercules (Plates 12 and 13). Their real and apparent dimensions will depend on their absolute dimensions or their distance from the Sun.

Towards the end of the nineteenth century Bailey, observing at the southern station of the Harvard Observatory at Arequipa in Peru, found, from his systematic photographic study, that variable stars appear very frequently in globular clusters. Shapley continued and extended Bailey's work, his contribution being notable for the great advances he made in our knowledge of these systems and in the study which followed, of the structure of the Galaxy. He divided the globular clusters into sixteen classes. In the first he placed the more concentrated clusters such as the one in Hercules, in the twelfth class he placed the more open clusters, almost devoid of a clearly defined centre. From the study of photographs obtained with the reflector at the Loiano Observatory, near Bologna (Italy), and that of Asiago, near Vicenza (Italy), Rosino was able to divide globular clusters into the following four different classes:

I. Clusters with very strong concentration, in which it is no

longer possible, with present available means, to resolve the stars near the centre. The star density diminishes rapidly towards the boundary of the cluster as, for example, in Messier 54 (M54).

II. Clusters with strong concentration. The central zone which is unresolved is nevertheless somewhat smaller than in the first group, and in photographs it is possible to distinguish the bright stars up to a few minutes of arc from the centre. As examples we have M3, M13, M30.

III. Clusters of moderate concentration. The very brilliant stars can be observed down to the centre, but, even with the largest telescope, the central zone can only be resolved with difficulty. The star density diminishes more slowly from the centre outwards. As example we cite M72, M56 and ω Centauri.

IV. Clusters with practically non-existent concentration. It is possible to observe, with large telescopes, an appreciable increase in concentration towards the centre. The red supergiants are rarely found in this class. They occur more frequently near the centre of the three preceding classes. Examples: NGC 7492 and NGC 5053.

Because of their peculiar characteristics, the clusters in the last class can only be identified with difficulty, but are probably very numerous.

Of the globular clusters for which the distance is known, it is possible to determine the integrated absolute magnitude and the linear diameter. By the integrated magnitude is meant the luminosity which the cluster would have if all the stars within it were concentrated at the centre. Investigations limited to about 30 clusters show that their mean absolute magnitudes appear to decrease with diminishing concentrations so that for the four classes enumerated above we have the following magnitudes:

$$\text{I. } -8^{m}\cdot 2;\ \text{II. } -7^{m}\cdot 8;\ \text{III. } -7^{m}\cdot 2;\ \text{IV. } -6^{m}\cdot 1$$

The measurements of the diameters of the clusters are somewhat uncertain because of the nature of the objects. The diameters from class I to class III vary from 70 to 50 parsecs with a maximum around 60 parsecs. A study of the variation of the star density as a function of distance from the centre of the cluster leads us to conclude that most clusters are not spherical in shape but appear to be more or less elliptical.

Because the Sun is not situated near the centre of the Galaxy, and because the various globular clusters are observed from this eccentric point, it is possible to study their distribution in space relative to the

well-defined centre of the Galaxy. This study reveals a strong concentration of clusters in a direction in galactic longitude $l = 327°$ and galactic latitude $b = 0°$. In this region of the Galaxy (Sagittarius), where the star density is greatest and where its centre is located, we also find the greatest number of globular clusters. These appear to lie chiefly in the galactic plane although some are also to be found at higher altitudes. In the direction opposite to the centre of the Galaxy, the clusters are very rare.

From the mean distances of the clusters we can deduce that the Sun is at a distance of about 26,000 light-years from the centre of the system of globular clusters. The majority of these are to be found in a sphere which has a diameter of about 80,000 light-years and which surrounds the Galaxy. In order to develop a theory of the origin and evolution of these clusters we require a knowledge of the star density derived from large-scale photographs, measures of radial velocity of the individual stars and comparisons between the various clusters. With the data available, Chandrasekhar has already made notable theoretical deductions. They indicate a slow but continuous loss of stars from such systems. He concludes that clusters never lose the more massive stars and that the loss of stars of smaller mass that do not attain a state of complete thermodynamic equilibrium is very small indeed. Moreover, if we take a mean mass for the individual components of the clusters, it appears that stars having 0·8 of such mass are most likely to escape.

As regards the stars forming a globular cluster, we can say with certainty that supergiants of classes O and B are completely absent. In the region of the Russell diagram, where between the giants and main sequence there existed a gap between classes A and G, there are to be found a large number of variable stars of absolute magnitude around zero, which are typical of these clusters. Red giants and supergiants are concentrated along a sequence which starts at about spectral class F5 and magnitude $+3$, and ends at spectral class G8 or K0 and magnitude around $-2{\cdot}5$. When the Russell diagram is completed by the addition of these stars it assumes the form shown in figure 34 in which we note, as in figure 9 (page 106), the distinction between population I and II and that the globular clusters are formed exclusively, or predominantly, of stars of population II.

Investigations on variable stars of these systems were begun by Bailey and have been continued by various eminent observers. In 1939, Sawyer published a list containing more than a thousand variable stars and new ones are continually being discovered.

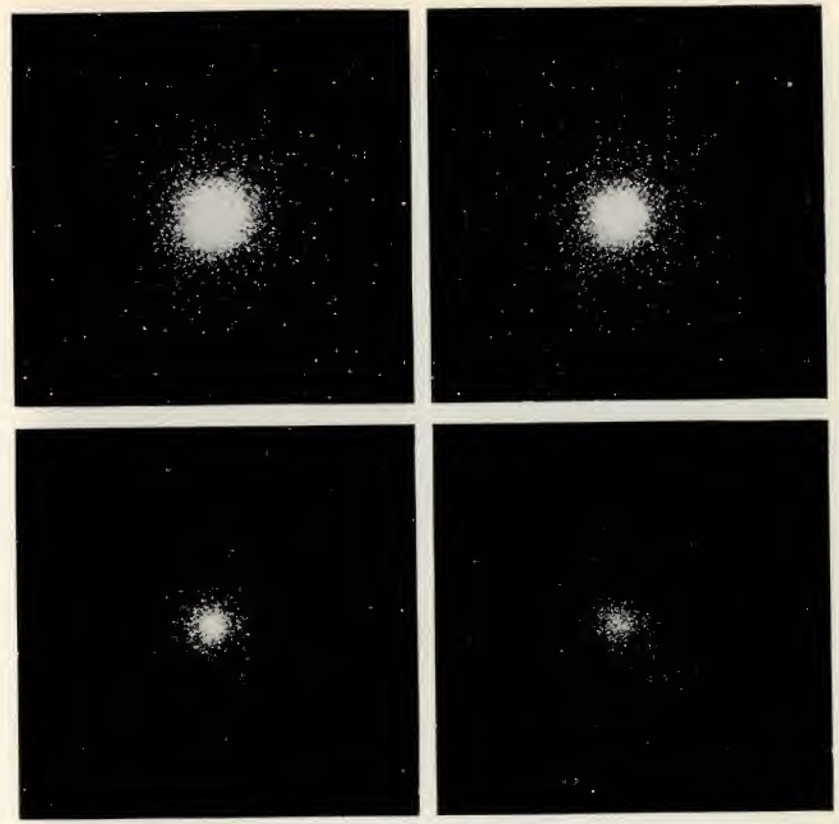


Plate 12. Star cluster in Hercules (M13). The four photographs were taken with exposures of 94 minutes, 37 minutes, 15 minutes and 6 minutes respectively. (Mt. Wilson Observatory)

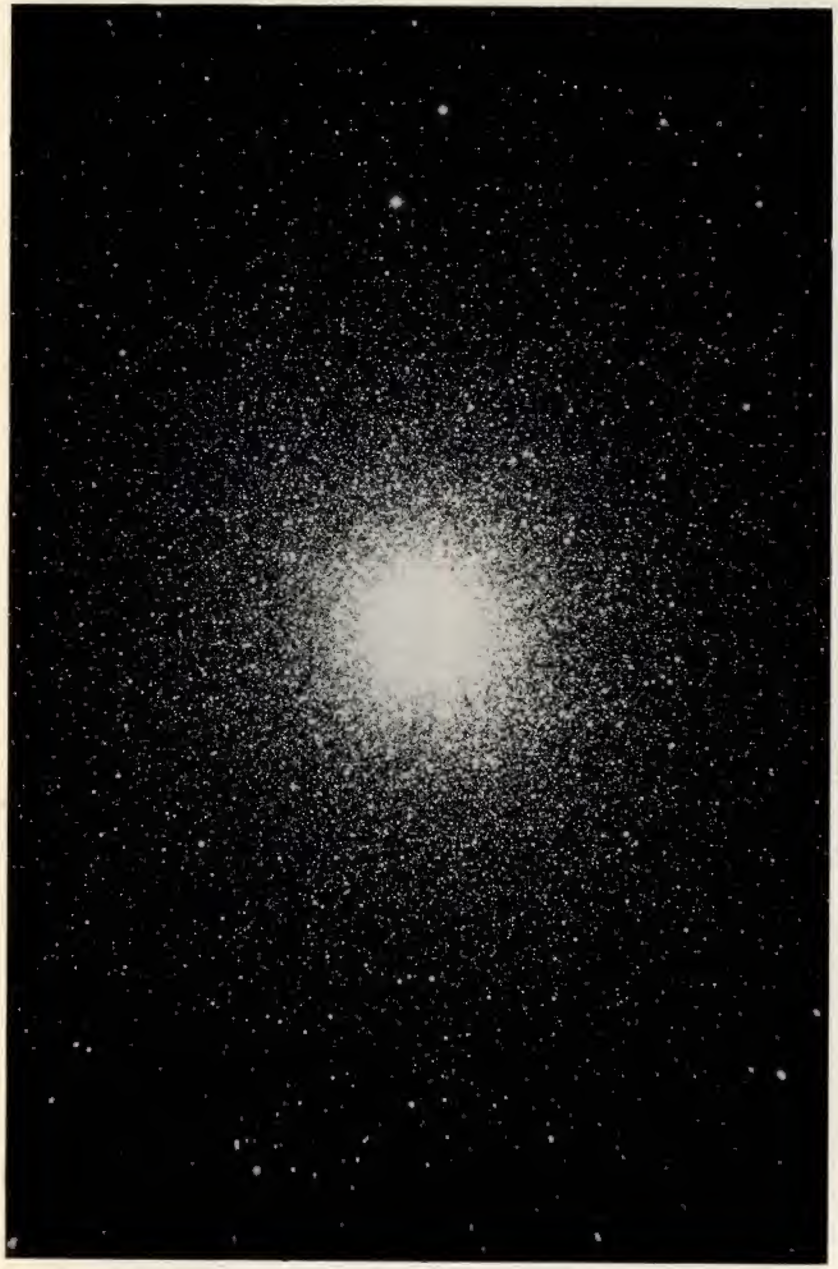


Plate 13. Star cluster in Hercules (M13). 200-inch Mt. Palomar

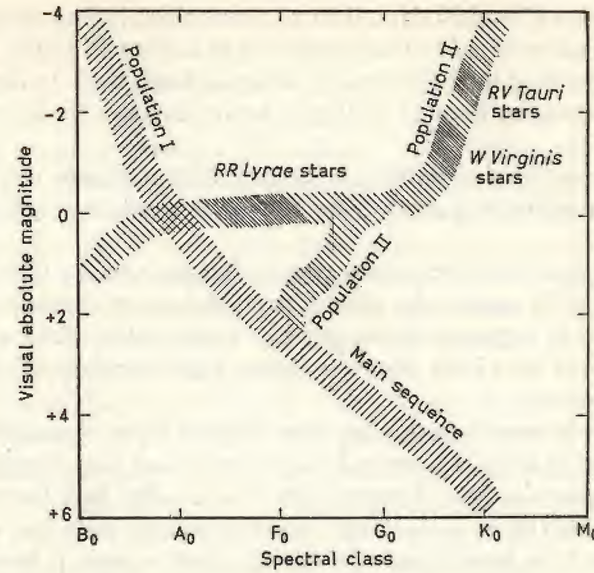


FIG. 34. Distribution of stars of population I and II according to their absolute magnitude and spectral class.

Rosino divides as follows the various types of variables which have so far been found in the globular clusters:

I. Cepheids of the type RR Lyrae with period less than a day. They are by far the greater number of the variable stars to be found in globular clusters. Their spectral type ranges from A1 to A8, with a photographic absolute magnitude of zero (a hundred times brighter than the Sun). Their position in the Russell diagram is shown in figure 34.

II. Cepheids with periods between 1·5 and 3 days. They are less common and appear to be a continuation of the preceding class. Their mean photographic absolute magnitude derived from the period-luminosity relation is —0·8 and their spectral type varies from A7 to F0.

III. Cepheids of the type W Virginis are peculiar stars with periods from 13 to 19 days. Their photographic absolute magnitude is —1·9, their spectral type is from F6 to G2. During their phase of increase in brightness emission lines of hydrogen are seen in their spectra, which are not observed in normal Cepheids.

IV. Semi-regular yellow variables and irregular red variables of the type RV Tauri appear to follow in the sequence. Their periods

are between 25 and 50 days, their photographic absolute magnitude attains a value of $-3{\cdot}0$, their spectral type is from F4 to G4. As the period increases the brightness of these Cepheids tends to diminish. Intense emission lines of hydrogen are to be seen during various phases.

V. Long-period variables of the type Mira Ceti are very rarely found in globular clusters. They attain an absolute magnitude of $-3{\cdot}3$.

VI. Novae, variables of the type U Geminorum. In 1860 a new star of the 7th magnitude, which corresponds to an absolute magnitude of -9, appeared in the globular cluster M80. Since then no other novae have been discovered, only a few variables of the type U Geminorum.

As can be seen from this list, very different types of variable stars are found in these clusters and their number can vary greatly from one system to another. For example, 185 variables have been found in M3 and 161 in ω Centauri. In other clusters only one or two variables have been found. On average their number is between 5 and 35. Variable stars of the type RR Lyrae form about 90% of the variables in the clusters. The other 10% consist of Cepheids of the groups II and III above, and yellow semi-regular variables.

In conclusion, the further study of the characteristics of these clusters will clarify their mode of evolution to a greater degree than is possible with the amount of data at present available. It seems certain that they consist mainly of dwarf stars, probably having mass and brightness of the same order of magnitude as that of the Sun or perhaps smaller. The presence or absence of variable stars of any given type and the frequency with which they occur must certainly be related to the age of the system and to the thermonuclear reactions which are responsible for their evolution.

Ambartsumjan has shown that apart from clusters and stellar groups, there exist also 'star associations' which have similarities with open clusters.

These associations of stars can be divided into two classes: the first containing very hot stars belonging to spectral classes O and B, and the second containing dwarf stars having a relatively low temperature. In the first of these classes are found large groups of very bright stars of spectral class O, which exist in our Galaxy and in the galaxies. In these galaxies they appear to be more common in the spiral galaxies, that is in those which are of comparatively more

recent formation, so that it would seem that star associations are closely linked to the structure of galaxies. Star associations are also found in the irregular galaxies. Associations of dwarf stars, on the other hand, are observed in the dark clouds of cosmic dust which contain irregular variables. The average star density in associations of stars of class O is smaller than that in open clusters, but their dimensions are much greater and star associations of this type may contain one or more open clusters. In associations of stars of spectral class O are found chains of stars, as for instance those which form the Orion belt, which can be thought of as being a nucleus of the association. Generally these chains of stars are enveloped by gaseous nebulosities.

Star associations are subjected to tidal forces which are produced by the general gravitational field of the Galaxy, and which tend to disintegrate the system. In clusters the gravitational interaction between the components is very strong and hence clusters are relatively stable, while, on the other hand, the disintegrating force in star associations begins to be felt soon after their formation.

According to Ambartsumjan, the time required by this process must be much shorter than the average age of the stars of the Galaxy, which is of the order of a few thousand million years. It must be concluded, therefore, that stars belonging to such associations must be of recent formation, and indeed are still in the process of formation.

From the study of the motion of the stars in these associations, it appears that the component stars recede from the centre with a mean velocity of about 6 miles/sec. We are therefore in the presence of a phenomenon of expansion. For instance, the association in Orion contains two expanding groups and others which must have been formed in different epochs. Originally these expanding groups must have had an extremely high density, possibly thousands of times that of the Sun.

In associations of dwarf stars there exist stars which have extremely irregular variations of brightness. We must conclude, therefore, that in them exist conditions of instability which are accompanied by processes of liberation of energy, not only in their central regions, but also in the outer layers of their atmospheres. Both types of associations are to be found generally in the galactic plane. Outside this plane we find systems which include globular clusters, Cepheids of type RR Lyrae and other variables. All these must be older objects, which must have an age greater than three thousand million

years and which have reached velocities sufficient to carry them far away from the galactic plane.

The information obtained from the research relating to star associations shows that the process of formation of stars is even at present still in progress both in the Galaxy and in the spiral galaxies. It also shows that stars are formed in groups, and that stars and the gaseous nebulae which accompany them are in expansion.

Part Two

THE PLANETS

CHAPTER I

The Constitution and Origin of the Solar System

The absolute dimensions of the smallest observable stars are comparable to those of the planets. For example, Barnard's star has very nearly the same dimensions as Saturn, while the companion of α Canis Majoris is only slightly greater than the Earth and van Maanen's star is about the same size as Mercury. On the other hand the temperatures are vastly different, the stars being self-luminous bodies. Stellar temperatures vary over a very wide range. White dwarfs, such as the companion of α Canis Majoris and van Maanen's star, are hotter than the Sun and have a temperature of 7,500° K, while on the other hand red dwarfs, such as Barnard's star and Wolf 359, have temperatures between 2,000° K and 3,000° K.

The planets reflect the Sun's light, and their surface temperature can be determined directly or calculated from their distance from the Sun. There is no evidence of radiation having its origin in the planets themselves. Thus, even if their dimensions are the same, the physical characteristics of the stars and of the planets are as vastly different as is their origin. It is probable that the planets in the solar system were either formed from the central star or else were formed at the same time as the star.

The solar system is quite different from anything else observed in the universe. As far as we can tell from our observations, systems of two or more stars have always fewer components than the solar system with its nine major planets and smaller bodies, such as satellites, asteroids and comets. Nor is it possible to discover, on account of the smallness of the bodies in the solar system, whether similar systems exist elsewhere in the universe. But as we have already mentioned above (see p. 119) the discovery has been made,

by indirect methods, of the existence of dark bodies which have dimensions comparable to those of the planets of the solar system, and which form part of other star systems.

The earliest task of astronomers, which was also one of practical importance in navigation, was that of determining with the greatest possible accuracy the orbits described by the planets, a problem of considerable difficulty since it depends on the intricate problem of three bodies. Fortunately, because of the smallness of the mass of the planets compared with that of the Sun, it is possible to proceed by successive approximations by calculating the perturbations of motions. These are caused by the reciprocal attractions exerted by the bodies of the solar system. By means of the study of perturbations it has been possible, gradually, to improve the tables for the calculations of the motion of the planets.

The planets are supposed to move in elliptical orbits the shape and inclination of which vary slowly, and which are subject to continuous periodic or secular perturbations. With time, the latter can radically change the character of the system. Celestial mechanics tells us that while the distances and the periods are less liable to change than other elements, even these undergo appreciable changes during long intervals of time comparable with the age of the solar system.

The general characteristic of the solar system is that the major planets move round the Sun in orbits which lie in approximately the same plane. Their sense of rotation around the Sun is the same; their orbits are nearly circular; their distances are related by a simple law; and finally, the Sun rotates in the same sense as the planets with its equator only slightly inclined to the plane of their orbits. All these facts have led us to conclude that the solar system must have had its origin in a common and well-defined cause.

Geophysical and astronomical considerations lead to the conclusion that the age of the Earth is probably between three and four thousand million years. We must suppose that the Earth and its solid crust were formed at that time, and it is generally thought that the creation of the universe must have occurred within the same limits of time. This hypothesis is based on the theory of the expansion of the universe and of the birth of the stars. However, it may be probable that the planets originated from the Sun when this was already formed.

Since it is impossible at present to discover other systems similar to our own, we must limit our study to the characteristics of the solar

system in an attempt to see if they can reveal the manner in which the planets, and possibly also the comets, were formed. Fundamental differences exist between planets and comets although some similarities can be found between the asteroids and comets. A study of the motion of these members of the solar system, of the form and position of their orbits in space, their distribution and their physical constitution has led to the formulation of various theories. As a result of progress both in our theoretical and observational knowledge, some of these theories had to be abandoned, while others appear to have a greater probability of being accepted.

The Sun's mass exceeds by a factor of 750 the total mass of all the planets. This is another substantial difference between the solar system and binary star systems for which, as we have seen, the differences of mass between the two components are not very great. When considering the origin of the solar system, we must take into account not only the difference in masses and physical composition but also the angular momentum. For a planet moving in a circular orbit around the Sun, the angular momentum is equal to its mass multiplied by its distance and its orbital velocity. By the principle of conservation of angular momentum the present rotation of the Sun, together with the revolution of the planets that surround it, should be the same as the rotation of the Sun before the birth of the planets. We find instead that 95% of the total angular momentum of the solar system is to be found in the orbital motion of Jupiter alone and only 5% in the remaining planets and the Sun. The latter, considered as a rotating body, contributes but a small part, namely 2%, and hence we must conclude that originally the Sun could not have possessed a rotation so large as to render its configuration unstable. Such an instability would be manifest as a flattening of the disc of the Sun and this is certainly not observed, though it is observable, for example, in the case of Jupiter which is nevertheless far from disintegrating. Because of this, astronomers had to abandon Laplace's hypothesis according to which solar disintegration, brought about by excessive rotation, gave birth to the planets.

On the other hand the evidence which has accrued from observations, and especially photographic observations, would appear to suggest that the stars were formed from spiral galaxies. It would therefore appear reasonable to suppose that the Laplace hypothesis should also be valid for the solar system, which is on a scale considerably smaller than that of the galaxies. In fact, the galactic nebular matter, which may be bright or dark according to the degree

of excitation of its constituent atoms, appears to lie in a plane of symmetry and to be highly condensed at the centre of these galaxies, which have the form of flattened ellipsoids terminating as spiral arms consisting of millions of stars. The formation of stars from spiral galaxies can take place, as is confirmed both by mathematical analysis and from observations. In the case of the solar system, however, the situation is very different. We are here in the presence of a system already formed without any trace of the hypothetical nebular material. In this case, theoretical considerations lead us to conclude that condensations like the planets cannot be formed in the equatorial plane of a star which is rotating and emitting gaseous matter.

Before considering those theories that have already been put forward to modify Laplace's hypothesis, let us consider the likelihood that the solar system may have appreciably changed from the time of its birth, and let us discuss further its physical and chemical properties.

The mutual gravitational attraction between the components of the solar system presents a problem which is both complex and practically insoluble. Nevertheless, because the mass of the Sun is so preponderant we can proceed by successive approximations. We begin by supposing that each planet moves in an elliptic orbit, the shape and inclination of which varies slowly, and for which only the secular variations are of interest during long periods of time. The centre of the orbit, its diameter, and the period of revolution are found to be practically unchanged although they may undergo slight changes of details. This demonstrates the stability of our system as far as gravitational forces are concerned, but there is the possibility that the approximate methods which we are forced to adopt may no longer be valid over long intervals of time such as the period of time from the origin of the solar system to the present day. For such periods of time, which are of the order of thousands of millions of years, some features of the planetary orbits may have been appreciably altered, especially their eccentricity and inclination, while the mean distances and periods may have been only slightly changed. It can be calculated that even for the asteroids which are subject to considerable perturbations, especially by Jupiter, both eccentricity and inclination of their orbits have undergone very little change for the greater part of the time. The planetary system, therefore, as a consequence of the smallness of its components, is stable, and so are also its sub-systems, namely the great planets and their satellites.

If the comets accompanying the solar system form an integral part of it they must be connected with its origin in some way. Both observations and theory show that comets do not come from outer space but are associated with the solar system. Their number must be of the order of several hundred thousands, and on average the same comets return to the neighbourhood of the Sun after thousands of years. Perturbations may change their orbits into hyperbolic orbits and, as a result, the comets will go further away in space and will be lost. The action of the radiation of the Sun on the tenuous matter surrounding the nucleus of the comets when they are in the neighbourhood of the Sun causes the emission of matter. This is evident from the fact that their tails develop in a direction away from the Sun. Thus comets are subject to a certain continual dispersal of matter which in the end limits their existence. The loss of gases and the length of the tail are both greatest soon after the comet passes perihelion, at which time the nucleus also attains its maximum temperature. These processes repeat themselves every time a comet returns into the neighbourhood of the Sun, and it seems reasonable to suppose that those of shortest period must become completely dissipated after many returns, unless the matter lost is but an infinitesimal part of the whole.

In the absence of any definite knowledge as to the mode of the formation of these celestial bodies so different from the planets, it has been suggested that they may have been captured by the Sun when it passed through a cloud of diffuse matter at a later stage. Alternatively comets may have the same age as the Earth and may have described orbits with large perihelion distances, larger, for instance, than Jupiter's orbit, and only a few, on account of perturbations, came into the neighbourhood of the Sun, thus becoming visible. Nevertheless the mystery remains, since neither this nor any other hypothesis has been able to explain the observations.

Let us now first consider, in a general way, what can be said about the density, the temperature, the atmospheric conditions and the composition of the various components of the solar system.

The Sun has a mean density 1·4 times that of water, while the planets, from Mercury to Mars and the Moon, have a mean density 3 to 5 times that of water. The other planets have a mean density about the same as that of the Sun, except Saturn, whose mean density is half that of the Sun. Hence these planets must be in a gaseous or liquid state in the outer regions and, if a solid core exists, it must be located deep down in the interior. The gases in the extended

atmosphere of these planets must in all cases be highly compressed in the inner layers so as to become liquefied. Jupiter's satellites and the Moon have densities which range from 1 to 4, so that the Moon and those satellites of Jupiter which have large densities must be made of rocks. Thus both the planets and their satellites exhibit notable differences of density which produce the external configurations that we observe.

As regards the temperatures of the planets, these are of an order quite different from that of the Sun, the internal energy of which is able to maintain a surface temperature of about 6,000°. The temperatures of the planets, on the other hand, depend entirely on the Sun's heat. It is now possible to fix, at the focus of large telescopes, highly sensitive thermocouples which enable us to measure the temperature either of the planetary surfaces as a whole, or of a particular point and to separate the part which is due to reflected sunlight from the radiations of longer wavelength which may be emitted by the planets themselves. Naturally, the nearer the planet is to the Sun the higher its temperature. Thus the sunlit hemisphere of Mercury has a temperature of about 400° C., while that of Venus is about 50° C. whereas its dark hemisphere has a temperature of —20° C. In the case of the Moon, the temperature of the sunlit part is about 120° C. while it is about —150° C. for the dark part. This provides another proof of the absence of an atmosphere around the Moon, and that the materials which form its surface are poor conductors of heat, like volcanic ash. The Earth, on the other hand, being protected by its atmosphere, is subject to much smaller changes of temperature, typified by the conditions produced by the Sun during the different seasons and in the various zones of the Earth's surface. The temperature of the equatorial zone of Mars reaches about 20° C. at 'noon' but falls well below zero at sunrise and sunset. Both Jupiter and Saturn have such low temperatures at the surface—they are of the order of —150° C., that it is difficult to measure them.

It is extremely difficult to measure any of the radiation from the outermost planets. It is possible to infer that the interiors of the greater planets are probably still at a high temperature, however little radiation in the region of long wavelengths is emitted from their external gaseous envelopes. During their passage from aphelion to perihelion the temperatures of the comets must undergo changes in temperature that are even greater than those for the planets.

Planets and their satellites generally present a measurable disc, and therefore observations of their surface, either directly or by

means of a spectroscope, show how varied are both the physical conditions and the composition of their atmospheres.

The Moon shows no trace of an atmosphere, and both Mercury and Mars have very rarefied atmospheres. Those of Venus, Jupiter and Saturn, on the other hand, are much denser.

We can explain why certain members of the solar system have atmospheres and others have not by considering the 'velocity of escape' and its effect on the molecules of their atmosphere. If the mean molecular velocity is equal to the velocity of escape, the gas can no longer be held down by the planet's gravitational forces and so diffuses into space. In the case of the Earth the mean molecular velocity of the constituent gases of its atmosphere is found to be much smaller than the velocity of escape, and as a result the atmosphere is retained. In the case of the Moon, still considering the velocity of escape, we find that an atmosphere of hydrogen would quickly be released, while in the present physical conditions of the Moon, an atmosphere of carbon dioxide would be retained, although if this had existed it would have been lost when the temperature of the Moon was much higher than it is at present. The larger satellites of Jupiter and Saturn, at their present temperatures, are just able to retain water vapour and all other gases denser than water vapour.

For the same reasons comets are unable to maintain an atmosphere and their nucleus must be formed of solid particles, as is clear from the fact that they can disintegrate into showers of meteors. Thus the gases, which are formed during the heating of the comet in its passage through perihelion, are lost into space.

Considering the mean velocity of the molecules of the various gases according to their weights, we conclude that the large planets must have atmospheres containing hydrogen compounds. The planets of medium size must have atmospheres containing compounds of oxygen while the smallest planets cannot have any atmosphere.

Of all the planets, the Earth is the only one for which we have any data for its external and internal constitution. The crust of the Earth, which has a thickness of nearly 37 miles, is composed of igneous rocks and, in a smaller proportion, of sedimentary rocks. The igneous rocks are solidified from magma, which is a liquid mass that has escaped from unknown depths; and by sedimentary rocks is meant boulder-clay and china-clay. If we study the chemical composition of the igneous rocks we can then compare it with the chemical composition of the other planets and of the stars. We cannot say, however, whether the magma flows out from natural reservoirs in which

it already existed in liquid form, or whether it originates in those parts of the Earth which are solid, on account of the high pressure existing there, but which melt when this pressure diminishes. The magma may be considered to be a complex solution of salts in water which contains various dissolved gases among which we find mainly water vapour, carbon dioxide, carbon monoxide, methane and others. The simplest elements number less than a hundred, while the Earth's minerals, which are derived as compounds from them, number nearly a thousand. The number of compounds, however, which constitute the greater part of the igneous rocks, more than 99% by weight, is limited and does not exceed a dozen. The major constituents of the igneous rocks are the oxides of silicon, aluminium, iron, magnesium, calcium, sodium, potassium and water. Silicon oxide forms 60% of the composition of the terrestrial crust, aluminium oxide forms 15%, and the others are found in decreasing proportions. The magma can either have solidified at great depth under great pressure, or else it has solidified rapidly and at low pressure near the surface as a lava flow. In the first case we have plutonic rocks and in the second effusive rocks. Differences in the conditions of solidification lead to differences in the mineral composition of the rocks. Both silicon and aluminium are relatively light elements and, like other light elements, are the more abundant in the terrestrial crust. The rare elements are the heavier ones.

If we now wish to pass to the study of the interior of the Earth we must have recourse to indirect methods such as the study of the propagation of Earth tremors, the consideration of the mean density, the magnetic state of the Earth and the composition of the meteorites. We thus arrive at a picture in which we have a central core in the Earth formed either of an iron nucleus nearly 4,300 miles in diameter, or possibly of a mixture of nickel iron similar to that which is found in meteorites. It has also been suggested that at the centre of the Earth are to be found the metals of the highest atomic weight either in their natural state, or as compounds, and surrounding them are to be found zones of nickel iron. The density of the central nucleus is nearly twice the mean density of the Earth, that is to say 12 times that of water. It is believed that its components, namely iron and the nickel iron, are in a molten state and compressed by the great weight of the overlying rocks, which also prevents cooling of the nucleus.

The general composition by weight of the Earth is, for the greater part, molten iron and dense rocks, and, in smaller proportions,

granite, sedimentary rocks, water and air. From the study of the chemical composition of the terrestrial crust, we deduce that only ten elements account for as much as 99% of the whole. Oxygen is the most abundant by weight, nearly 50%, then follows silicon with 25%, and then, in this order, aluminium, iron, calcium, sodium, potassium, magnesium, titanium and hydrogen with only 0·13%. The rocks lying over the crust, or at least those which are brought to the surface following eruptions, are richer in iron and magnesium and poorer in aluminium and silicon.

Meteorites are thought to have a similar composition to that of the Earth's nucleus. They can be divided into three groups, namely 'stony', 'metallic' and 'stony-metallic'. To the stony meteorites belong the majority of the meteorites which have fallen on the Earth, and they consist mainly of silicates. The metallic mass of the metallic meteorites consists mainly of iron and nickel in various proportions, the amount of iron ranging from 60% to 95%. The stony-metallic meteorites are of an intermediate type consisting of the two materials in roughly equal proportions. The main constituents of the stony meteorites are olivine and pyroxenes, that is to say, the first minerals produced during the crystallization of the terrestrial magma. In addition there are also minerals which are not found on the surface of the Earth, such as iron carbide, iron nickel phosphide and others. The existence of these can be explained as being due to the much higher temperature at which the mineral was formed, as was suggested by Gallitelli in his work on meteorites.

Thus it is clear that there are differences in the process of formation of meteorites and of the surface rocks of the Earth, even though there are remarkable analogies between them. The absence of mineral hydrates in meteorites shows that in their composition there must have been great scarcity or a complete lack of water in the original molten mass, so as to lead us to believe that the stony meteorites were formed from molten masses which had a very low water content. In the rocks of the terrestrial crust we find indications of phenomena of hydration, but at great depths there must be, in general, magmatic masses with very poor water content, and this suggests that there is a close similarity between the composition of the meteorites and that of the interior of the Earth.

Since we find a similar percentage of iron and nickel in the composition of both the Sun and the meteorites, we must conclude that in the meteorites and in some members of the solar system there exists a composition common to all, probably resulting from the

condensation which followed the gaseous phase and which could well be that actually observed in the Sun. Owing to the large preponderance of free hydrogen the metallic compounds, which can be reduced by hydrogen, have separated as metals, while the oxides, which cannot be reduced by hydrogen, have produced the silicates.

The study of the composition of the Earth and of the meteorites leads to the conclusion that the meteorites are fragments of an object of the solar system which disintegrated for some unknown cause, probably at the time when the Earth was formed. We have proof of this from studies (see p. 321) of the age of meteorites, their formation and cooling. This age, which is calculated from the quantity of helium and radioactive elements of the uranium-radium series contained in the meteorites, appears to be of the order of some thousand million years, the same as that for the rocks of the terrestrial surface. Other investigations on the radioactivity of potassium in meteorites and on the Earth lead to the same conclusion.

In the Sun, as in the Earth, the same metals, primarily iron, magnesium, sodium, potassium and aluminium, are more abundant than all the other elements, so that the light elements, such as lithium, beryllium and scandium, are as rare on the Sun as on the Earth. This similarity of composition lends support to the hypothesis of a common origin, or, in other words, that the Earth originated in the Sun. Alternatively we may suppose that the relative number of atoms of different types is the result of a general process of formation or disintegration of the atoms which, once started, attains the same final stable state. The similarity, however, is somewhat restricted because hydrogen, carbon and nitrogen are far more abundant on the Sun than on the Earth. This applies also to helium, which is an abundant element on the Sun, but is only found in very small quantities on the Earth.

From observations and from theoretical considerations we can conclude that, compared with the Sun, the Earth has much smaller quantities of those elements which form the atmosphere, so that the Earth must have lost a large amount of its atmospheric gases. The Moon has completely lost its atmosphere, Mars has a smaller one than the Earth, while in the case of Saturn its atmosphere is extensive. It contains various gases, and this proves that the extensive atmosphere for the various planets increases proportionally to the velocity of escape, which depends on the ratio of the mass to the radius of the planet.

If we suppose that the Earth had been hot for a relatively short

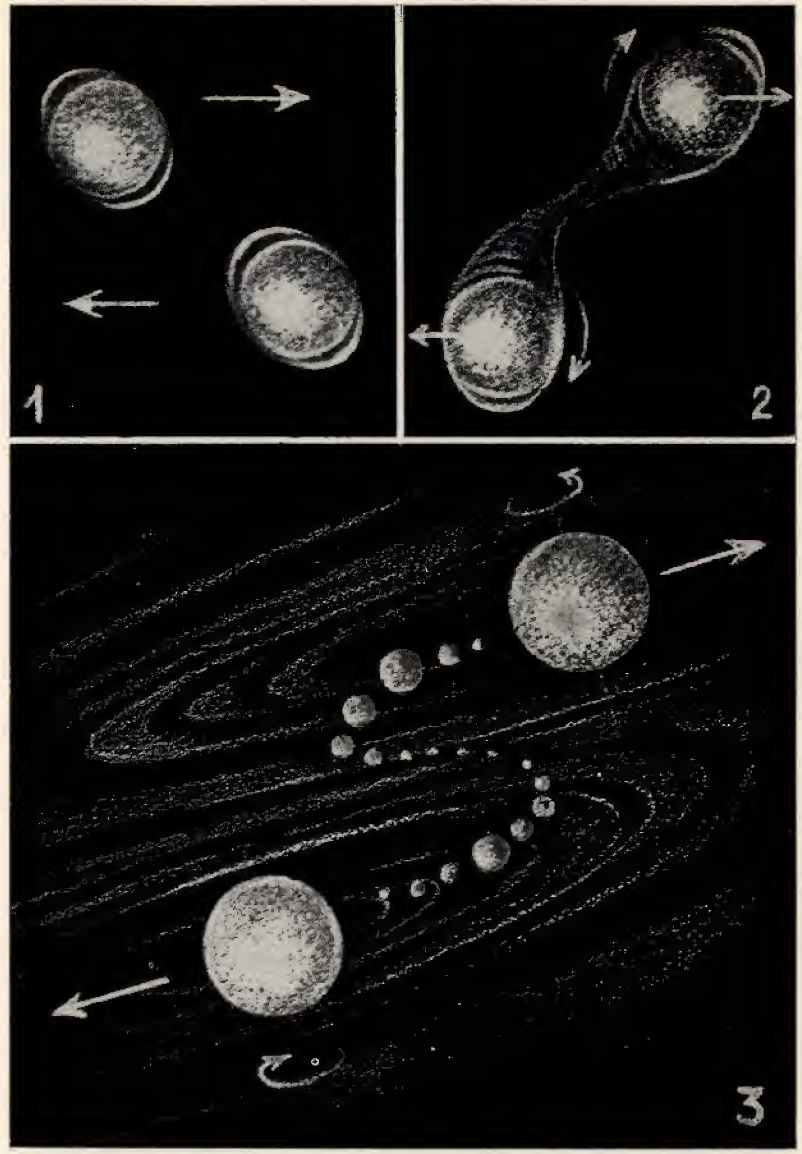


Plate 14. Theory of the birth of planets from a filament of gas detached from two suns. (1) approach of two stars and development of tides (2) formation of gaseous filament (3) development of planetary systems

time, it is possible to explain how it has lost certain gases such as oxygen, nitrogen and free hydrogen in great quantities while retaining water and carbon dioxide which could have been absorbed by molten lava. In this way we can explain how it was possible for a solid body like the Earth to be formed, by very rapid cooling from a gaseous body like the Sun. Such a solid body would contain heavy elements and would have lost a considerable amount of hydrogen.

From the spectroscopic study of the planetary atmospheres we can infer the presence of various gases in those atmospheres. Thus the spectrum of sunlight passing through our own atmosphere reveals the presence of oxygen and water vapour bands. Since the temperature of the Sun is much too high for such molecules to exist, their presence must be due to our own atmosphere. In the case of the other planets it is difficult to separate in their spectra these bands from the terrestrial ones. Attempts have been made to do this, using spectrographs with high dispersion when the distance of a planet from the Earth changes rapidly enough for the Doppler effect to be utilized. In the case of Venus and Mars we find that both the oxygen and water vapour are extremely rare in the two atmospheres. Other gases are found, especially in the cases of Jupiter and Saturn. Planets having masses of the order of Jupiter and Saturn are able to retain even the lightest gas, and thus in their extended atmospheres, which are composed mainly of hydrogen, we also find hydrogen combined with other elements giving such compounds as methane, ammonia and water. It is certain that the planets were not formed by the accretion of small bodies, otherwise these would have lost their hydrogen and other light gases, and therefore the nucleus must have had its present dimensions from the very beginning.

The conclusion which we can draw from the study of the physical and chemical properties of the bodies of the solar system is that they must have been formed in some way from a body having a very high temperature and a composition similar to that which is observed in the outermost parts of the Sun, and that subsequently they underwent a very rapid cooling.

As we have already mentioned, Laplace's hypothesis, simple and attractive though it is, does not survive the modern criticism, therefore other theories have been put forward in which some exceptional event is postulated and which is supposed to have taken place in the Sun at a time of the order of several thousand million years ago which appears to be the age of the solar system. Such an explanation must be considered unsatisfactory because the order and the time

sequence in which celestial phenomena occur make it less likely that exceptional events could have taken place rather than those which follow a general evolution. Thus, when the distances, dimensions and masses of the various bodies of the solar and sidereal systems became known, it was realized that the Earth was not a privileged body either with respect to the Sun or with respect to the rest of the universe.

On the other hand, frequent phenomena which occur in relatively short intervals of time, almost instantaneously in the scale of the universe, such as the explosion of novae, are common and may even assume periodic characteristics. In this case, as we have already said, we are dealing with a real stellar cataclysm, during which a great quantity of matter is ejected from the central star. Part of this matter, as observations show, remains as a nebulosity within the gravitational field of the nova.

It is not improbable, therefore, that an exceptional event might have taken place in the case of the Sun, which might have undergone such a cataclysm, and as a result, produced a nebula. Within this nebula were formed bodies which were similar to those of the solar system, and which had cooled rapidly, while the nebula itself had dispersed, or else had produced the comets.

In order to explain these exceptional events, various astronomers, and in particular Jeans, developed the 'tidal theory' which could account for the observed facts. Tidal actions are present in celestial bodies on a scale which is far greater than that occurring between the Earth and the Moon. These tidal actions, which may have some influence on the formation of other bodies, are observed in certain galaxies which have filaments or matter escaping from the nucleus, or from the spirals of the central nebulosity, and which appear to be subject to gravitational forces. Tidal actions are also observed in the case of galaxies which are sufficiently close to each other to exert an influence on one another. The filaments appear to break up into a number of separate masses which may well evolve as separate stars.

A similar event may have occurred in the case of the Sun, though on a much smaller scale, if a passing star of greater mass had come close to it, in the distant past. Taking into consideration the relative velocity of the two stars, their minimum distance and their relative masses, Jeans suggested that a gaseous filament became detached from the Sun by tidal action and that thereafter this filament condensed into separate masses. These condensed masses, cooling at

different rates, are thought to have formed the planets which we observe (Plate 14). In the initial stages, and under the influence of the gravitational forces of the two stars, the planets would have described very complicated orbits, but subsequently, once the star of greater mass had gone further away, the planets would have settled down to elliptic orbits around the Sun, although experiencing a resistance to their motion during their passage through the gas left behind in the surrounding space after the cataclysm. The long-term effect of this resistance would be to make the planetary orbits very nearly circular while at the same time the gaseous mass would have dispersed by degrees. The remains of this gas may perhaps be found in the small dust particles which give rise to the zodiacal light which can be seen in the plane of the ecliptic in the neighbourhood of the Sun.

It is probable that the gaseous filament emitted from the Sun at the moment when the tidal action was greatest may have been cigar shaped, that is to say thicker in the middle and thinner at the ends, so that when the condensations began to form, those from the middle of the filament attained greater dimensions than those at the ends, as is the case of the solar system, where Jupiter and Saturn are to be found in a central position with reference to the other planets. Jupiter, which has dimensions and mass greater than those of the other planets, would therefore have once formed the central part of the filament. Between Jupiter and the Sun we have the asteroids, which may well be the result of the disintegration of a single planet, followed by Mars, the Earth, Venus and Mercury, which is the smallest of the planets. On the other side of Jupiter, away from the Sun, we find Saturn, Uranus, Neptune and Pluto, which have dimensions decreasing with increasing radial distance from the Sun. In this connection it is of interest to note that Jeans's theory was put forward many years before the discovery of Pluto, and the presence of this planet confirms the theory.

We have seen that the great difference in mass between the Sun and the planets is the fundamental characteristic which distinguishes the solar system from binary systems. In the case of the planets and their satellites we have similar large differences in mass. Indeed in the case of both Jupiter and Saturn, we find that the distribution of mass among the various satellites is similar to the general distribution of mass in the solar system. This points to an origin of the satellites similar to that of the planets. During the evolution of these, Jupiter and Saturn must have cooled much more slowly than the minor

planets and must have remained in liquid or gaseous state for a longer time. The orbits of Jupiter and Saturn were not yet finally established, and if these two planets had approached the Sun they could have been influenced by a strong tidal action, so that filaments were extracted similar to the one which the hypothetical passing star extracted from the Sun. Such filaments, on condensing in separate masses, could have given rise, on a much smaller scale, to a new generation of celestial bodies, such as the satellites.

This theory appears to explain not only the formation of the satellites but possibly also the fact that Jupiter and Saturn have respectively twelve and nine satellites while Mars has only two. The Earth has only one satellite with a mass not as small as that of the others, and Venus and Mercury have none. Amongst the outer planets, Uranus has five satellites and Neptune has two, one of which is relatively large.

In fact, since the smaller planets attained the solid state rapidly it must have been more difficult for matter to be ejected from them. If this were the case, the masses which were produced by the tidal action would not have changed very much. The Earth, with a single satellite, must have become partly liquid and partly gaseous after the cataclysm which generated it. Mercury, Venus and Pluto must have been in liquid or solid form immediately after their birth. Mars, Jupiter, Saturn, Uranus and Neptune, on the other hand, were born in the gaseous state, and while in this condition must have lost the matter which gave rise to their family of satellites.

In the case of rotating galaxies, we have some notable examples which confirm the old theory put forward by Laplace. The matter which is symmetrically distributed with respect to the equatorial plane, continues to remain there even when it recedes from the centre of the galaxy. In the case of the Sun, although the inclination of the planetary orbits to the equator of the Sun does not exceed 6°, we cannot claim that this constitutes a plane of symmetry. Thus, we cannot accept Laplace's theory to explain the origin of the solar system. In the case of the tidal theory it is possible to imagine that the planets describe orbits lying approximately in the plane in which the filament was extracted at the moment that the hypothetical passing star came into the neighbourhood of the Sun. Incidentally we may argue here that a similar effect might have been produced if the Sun had exploded like a nova, provided the explosion had taken place in a region in the neighbourhood of its equator. In any case, as Jeans points out, it is the gravitational instability which, in the

first instance, is responsible for the creation of the celestial bodies, whether stars or planets.

With the exception of the satellites, the probable origin of which we have discussed already, there are in the solar system bodies which are very small compared with the major planets, namely the asteroids which are found between Mars and Jupiter, the comets and the particles forming the rings of Saturn and meteors. These bodies, perhaps with the exception of the comets, most probably belong to swarms produced by the disintegration of larger masses, since they appear to be too small to have originated from the gaseous state. The asteroids may be thought of as the remaining fragments of a planet which once existed between Mars and Jupiter, while Saturn's ring may be supposed to be the remains of one of its satellites. Finally, shooting stars, or meteors, may be fragments of disintegrated comets.

Since it has been proved that the age of the meteorites which have fallen on the Earth is of the order of the age of the Earth itself, it follows that such swarms of bodies must have been formed at the moment when the great tidal wave was produced which gave rise to the solar system. Roche proved mathematically that a satellite is able to describe its orbit undisturbed, so long as its distance from the central planet exceeds a certain limit called 'Roche's limit'. If the distance becomes less than this, the satellite breaks up. This limit is nearly two and a half times the radius of the central planet. In fact, the radius of the most external of the rings of Saturn, and the radii of the orbits of the satellites nearest to Jupiter and Mars, appear to be of this order. The nearest satellite to Jupiter is very close to Roche's limit. Even our Moon, which according to theory will gradually approach the Earth, will finally be disrupted, and may end up as a ring around the Earth. Disintegration of various comets has actually been observed, and we have reason to believe that the phenomenon must have occurred because such comets entered the critical zone when approaching the Sun. In the case of the asteroids it is thought that, after the formation of the solar system, when the orbits of the planets had not yet settled into their almost circular forms, the planet which occupied the 'missing' position between Jupiter and Mars may have come repeatedly close to Jupiter and, according to Roche's theory, disintegrated as a result into the asteroids which we have today.

However attractive this theory may seem, it is not free from criticism. Russell points out that the hypothetical star must have

passed very near to the Sun to produce the required tidal action, and that the angular momentum in the filament extracted from the Sun could not have been of the order of the angular momentum that we find in the planets. Moreover, even in the components of binary systems, we can see strong tidal actions of varying intensity taking place on account of their eccentric orbits, yet there is no indication of matter being emitted from their components. Furthermore, the stars are distributed in space at such distances from each other that an encounter, or even a single approach of two stars is highly improbable, and if this did happen, then our solar system is an exceptionally rare case.

The theory of the expansion of the universe is based on the supposed recession of the galaxies and it is evident that in some remote time the relative distances of the celestial objects would have been smaller and the encounters or approaches of two stars would have been more probable than at present.

In the light of recent theoretical studies, the tidal theory has been practically abandoned while a return to the theories of Kant and Laplace seems to have met with some favour, though these theories have to be greatly modified to take account of modern ideas, as, for example, has been done by Weizsäcker. According to his hypothesis, before the solar system was born, the Sun was surrounded by an envelope of gas and of cosmic dust which formed with it a rotating system with the Sun as centre. The envelope of gas had dimensions comparable to the solar system, whereas its mass did not amount to much more than about a tenth of that of the Sun. Remembering that the cosmic matter is essentially composed of hydrogen and helium while the heavier elements are only found in small quantities, it seems likely that the envelope of cosmic matter rotating around the primeval Sun, underwent rapid flattening on one plane (fig. 35) on account of the collision between the elements that moved in various planes. The gravitational attraction, acting between the various points of this diffuse disc, may have been the origin of the condensation of the various planets. According to Weizsäcker's hypothesis, the dust particles made of the heavier elements must have condensed in elliptic orbits rotating around the Sun while undergoing frequent collisions, while the part of the envelope consisting of helium and hydrogen was gradually dispersing. Weizsäcker has shown that rotating vortices will be formed during the combined motion of the gaseous mass and of the dust particles undergoing condensation. The periods of these vortices are short for those lying

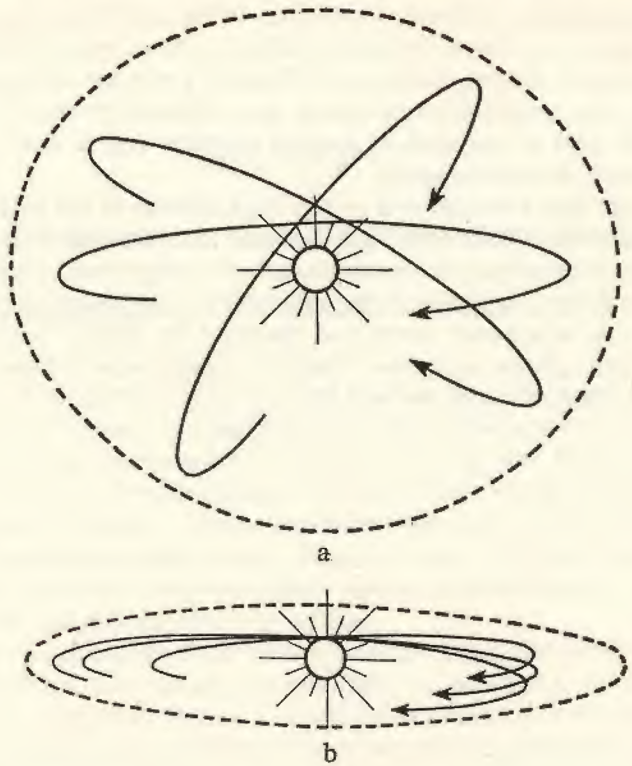


Fig. 35. (a) Diffuse, interstellar matter rotating in various planes around a central body. (b) Under the action of collisions between small particles, all the matter is flattened into a disc around the central body. (Gamow.)

close to the Sun and longer for those further away from it. In the interior of the vortices, the agglomeration of dust must have occurred very rapidly with a consequent increase in the dimensions of the planets. From a theoretical discussion of the properties of the nebula which gave rise to the solar system, he was able also to calculate the dimensions of the various planets of the solar system, finding that their dimensions are smallest near to and furthest away from the Sun, and greatest for intermediate distance, such as is in fact the case. Furthermore, he was able to give a plausible explanation of the regularity of the mean distances of the planets from the Sun (see p. 233).

This hypothesis is certainly very attractive, particularly as it explains the reason for the varied chemical composition of the

various planets. Mercury, Venus, the Earth and Mars are rocky, since their mass has never been sufficient to attract much interstellar gas. Jupiter, Saturn, Uranus and Neptune are liquid and gaseous, since their gravitational attraction was sufficient to retain a substantial part of the original gaseous envelope before this became dispersed throughout space.

From what has been said in this brief account of the hypothesis and theories of Weizsäcker, it is clear that the theory has wide applications in cosmogony for systems outside the solar system. According to this theory, the origin of the solar system is no longer considered to be an exceptional event and therefore an infinite number of planetary systems may exist. There is already some evidence that such systems do exist (see p. 116).

CHAPTER II

The Distance of the Planets from the Sun

The motions of the planets around the Sun are governed by the three laws of Kepler, and the planets may be divided into two groups according to their size and their distance from the Sun. Near to the Sun we have the smaller planets: Mercury, Venus, Earth and Mars. At a greater distance, and separated from them by the zone occupied by the asteroids, we find Jupiter, Saturn, Uranus, Neptune and, still further away, Pluto which was discovered in 1930, and which, so far, is still the last planet of the solar system.

When the distances of the planets from the Sun, and those of the satellites from their planets, are examined, we find that they exhibit a certain regularity. This, if it could be explained by the laws of physics, might provide us with further information regarding the origin of the solar system. In the past various astronomers have, on several occasions, suggested empirical laws which aimed at representing the mean distances of the planets from the Sun. The first was proposed as long ago as 1766, by Titius, and among the more recent ones we have that proposed by Armellini (1917). Silva has shown that these laws may be expressed in the general form:

$$x_n = a+bc^n \qquad (1)$$

where x_n represents the mean distance of the planet from the Sun; n is a whole number which generally increases by one unit in passing from one planet to the next; and a, b, c are three constants.

In the case of the two laws mentioned above, we have:

$$\text{Titius} \quad x_n = 0{\cdot}4+0{\cdot}3\times 2^n$$
$$\text{Armellini} \quad x_n = 1{\cdot}53^n$$

If Silva's equation, given above (1), is rewritten for $n+1$, and then divided by the original, we have:

$$\frac{x_{n+1} - a}{x_n - a} = c$$

which expresses the fact that 'the ratio of the mean distance of two successive planets from a sphere of given radius and having its centre at the Sun is constant'.

For $a=0$ the statement of the problem is simplified, and may be applied not only to the planets, but also to the majority of the satellites, as follows: 'the distances of the planets from the Sun, and those of the satellites from their planets, are in geometric progression'. There are, however, gaps in the terms of the progression which break the supposed regularity of these and other similar laws.

CHAPTER III

Mercury

Mercury, being the nearest planet to the Sun at a mean distance of 36 million miles, receives more solar light and heat than all the other planets, and has other characteristics peculiar to itself. The eccentricity of its orbit is 0·21, and the inclination of its orbit to the plane of the ecliptic is 7°. Its diameter is 3,100 miles, its mass is 0·05 times that of the Earth, its volume 0·06 times that of the Earth, and both are smaller than those of any other planet. Its specific gravity is 3·8 and it revolves around the Sun in a sidereal period of 88 mean solar days. As seen from the Earth, its apparent diameter varies, according to its distance, from 5″ to 13″, and its apparent magnitude from $+1^{m}\cdot1$ to $-1^{m}\cdot2$, thus at times being almost as bright as Sirius. The 'albedo' for Mercury is 0·07. By albedo we mean the ratio between the total quantity of solar light that is reflected by the planet in all directions, and the quantity that actually falls on it.

During the course of its journey around the Sun, Mercury passes through various phases, as do Venus and the Moon. When at its maximum elongation its apparent shape is that of a large crescent, whereas it would be expected to have the same shape as the Moon at first quarter. This is due to the relative faintness of the terminator as compared with the brighter limb, an effect which becomes more noticeable when Mercury is observed in full daylight.

Mercury is the only planet whose motion does not conform with the laws of universal gravitation, and there are still marked discrepancies between its predicted motion and its observed motion.

Little is known of the physical conditions of Mercury in spite of the regular and systematic observations by Schiaparelli. Owing to its proximity to the Sun, which restricts its observation to the hours of twilight or of broad daylight, Mercury is not an easy object to

study. Nevertheless, in 1881, Schiaparelli initiated a series of regular observations with the two Merz refractors of the Brera Observatory, which he also used for observations of Mars, and eight years later he announced the existence of bright and dark spots on Mercury. These were observed in the same positions on consecutive days and at various times, showing that the planet must revolve around the Sun more or less in the same manner as the Moon revolves around the Earth, or Iapetus around Saturn, that is to say, always presenting the same hemisphere to the Sun. The rotation period of Mercury is, therefore, the same as its revolution period, that is 88 days; but, owing to the large eccentricity of its orbit, there will be a marked 'libration' in longitude. Because of this, Schiaparelli was able to observe that the spots periodically approach and recede from the eastern and western limits of the dark hemisphere.

During those years Schiaparelli drew the first map of Mercury, which shows the dark markings as extremely thin bands of shadow, which are therefore difficult to identify on the surface of the planet. Their red-brown colour differs little from the general tint of the disc, which varies from a clear pink to copper. Although the markings are constant as regards position and shape, their intensity is variable. In the vicinity of the limb they disappear altogether, and this would suggest the presence of an atmosphere; furthermore, their variable degree of visibility, when at the centre of the disc, also suggests the occurrence of condensations of vapours. The bright markings last for several days in the same position, and are for the most part very bright when seen near the limb of the planet. They may perhaps be produced by condensations of varying density which are formed in the atmosphere of the planet.

The existence or non-existence of an atmosphere on a planet depends upon the velocity of escape of the gases which compose it, and hence on the ratio between the mass and radius of the planet. If the velocity of escape is sufficiently low, the atmosphere will be dissipated rapidly. The velocity of escape for Mercury is 2·4 miles/sec.; this, in conjunction with the mean temperature of the planet, means that it cannot retain an atmosphere consisting of light gases, but only of the heavier ones such as carbon dioxide and oxygen. The study of the blue and infrared regions of the spectrum of the planet that have been made at Mt. Wilson have failed to reveal any absorption lines or bands that can be attributed to a possible atmosphere on Mercury. Whatever the final conclusion may be regarding the atmosphere of Mercury, there is no possibility of the existence of life as we know it

on Earth, especially when we consider the extremes of temperature to which its surface is subject.

Mercury's libration, which causes it to oscillate back and forth through an angle of 47°, has an important effect upon its physical condition, since the various parts of its surface are continuously, or intermittently, illuminated by the Sun, or are in total darkness. His systematic observations of the surface markings convinced Schiaparelli that the atmosphere of Mercury must be less transparent than that of Mars, and more nearly like that of the Earth. In any case it will readily be understood that the conditions of life are utterly unlike those on our planet, even when account is taken of the fact that the great difference of temperature on the sunlit and the dark regions must induce a very active circulation of the atmosphere, such as might set up a temperature equilibrium even more perfect than that occurring on the Earth.

If it is assumed that Mercury behaves as a black body, Stefan's laws allow us to calculate its mean temperature, and this is found to be about 200° C. Direct measurements made by Pettit and Nicholson with a sensitive thermocouple in an evacuated cell mounted at the focus of the Mt. Wilson 100-inch telescope gave a temperature of 420° C. for a zero phase angle, 330° C. at a phase angle of 90°, and 230° C. at a phase angle of 120°, when the phase is that of the smallest observable crescent. Although these figures refer to the integrated radiation, we may conclude from them that the temperature variations between night and day are less abrupt than would occur with a long rotation period. This conclusion, together with the uncertainty involved in the observation and identification of the markings on the surface of Mercury, has cast some doubt on its slow rotation. The strong effect of libration, tending to reduce the temperature variations, must not be forgotten, nor that the thermocouple measurements are only approximate. Finally, the period of rotation determined by Schiaparelli has recently been confirmed by Antoniadi's accurate observations of the peculiarities shown by the surface of the planet.

The comparison of the albedo of Mercury with that of various terrestrial substances suggests that its surface may consist of lava similar to that of our volcanoes, and, indeed, the Moon has the same albedo and the same proportion of infrared radiation to total reflected radiation. The variations of brightness during the various phases are the same both for the Moon and for Mercury. Maximum brightness is reached for a zero phase angle, and minimum

brightness when the planet appears as a fine crescent (phase angle 120°). The limbs of the two bodies are also brighter than their central regions.

Father Secchi had noticed that Mercury is less bright towards its terminator, and in recent years Lyot has shown that this contributes to the difficulty of finding the planet in full daylight when it is near inferior conjunction. Lyot determined the polarization curve of Mercury with a very sensitive polarimeter, and found that it closely resembles that of the Moon and is exactly intermediate between that for the first and last quarters. When Lyot compared his observations made at Meudon Observatory and the Pic-du-Midi under varying conditions of visibility, with those obtained in the laboratory, he was able to confirm that the surface of Mercury is probably covered with dust similar to terrestrial volcanic ash. The regularity of the variations undergone by the polarization of the light of Mercury observed at various phases and the exact similarity with those observed in the case of the Moon, also proves that its surface cannot be covered by clouds similar to those in the atmosphere of the Earth. If the bright markings which were observed by Schiaparelli and Antoniadi and which vary, both in position and intensity, were clouds, Lyot suggested that they must consist of particles of dust from the surface of Mercury, with a size considerably larger than the wavelength of light.

Because of the inclination of its orbit to the plane of the ecliptic, Mercury usually passes above or below the Sun at inferior conjunction, but when the conjunction occurs in the vicinity of the nodes, Mercury can be seen as a small dark spot crossing the disc of the Sun (transit of Mercury). Since the heliocentric longitudes of the nodes are 47° 23′ and 227° 23′, which the Earth passes on November 9 and May 7 respectively, transits of Mercury can only occur around these two dates. The duration of the transit varies between wide limits, namely from a few minutes to nine hours, according to the length of the chord that it traces across the solar disc, and according to its orbital velocity. Transits are important as a means of correcting the position of the planet, and hence the elements of its orbit.

CHAPTER IV

Venus

Venus is the brightest and most conspicuous object in the heavens, and being situated, like Mercury, between the Earth and the Sun, can be seen in the neighbourhood of the latter in the morning or in the evening. It is visible with the naked eye during the day when it is near its greatest elongation. It is at a mean distance of approximately 67 million miles from the Sun, and receives from it exactly double the amount of heat and light that the Earth receives. Its mean orbital velocity is 21·7 miles/sec., and its eccentricity, 0·007, is smaller than that of any other planet, so that its orbit can be considered to be practically circular. The inclination of the orbit to the ecliptic is 3°·4, the diameter 7,704 miles, its mass 0·82 and its volume 0·92 times those of the Earth. The specific gravity of Venus is 4·86 and the planet revolves around the Sun with a sidereal period of 224·7 mean solar days. The apparent diameter ranges from about 64″ at the time of inferior conjunction, to 10″ at the time of superior conjunction, due to the fact that the distance of Venus from the Earth varies greatly, and as it passes through the various phases discovered by Galileo, its magnitude varies from $-4^{m}\cdot 3$ to $-3^{m}\cdot 3$.

Except for the Moon, and occasionally an asteroid or comet, no other heavenly body approaches the Earth as closely as Venus, its minimum distance from it being about 26 million miles. Venus is both the 'evening star' and the 'morning star', Hesperus and Phosphorus of the Greeks, although since the time of Pythagoras it was known that both were the same celestial object.

The phenomenon of the phases of Venus about which Galileo had argued with one of his favourite pupils, Father Castelli, had attracted Galileo's attention early in his astronomical observations. As a result of these observations he no longer had any doubts about

the reality of the motion of Venus, nor of all the other planets, around the Sun. Galileo observed and made drawings of Venus which, when it appears 'horned', has a disc forty times as great as when it is 'full', on account of its varying distance from the Earth.

Galileo also concluded that Venus was by nature 'dark', as had been firmly held by the Pythagoreans, the Copernicans, by Kepler and by himself, but this fact was first ascertained by his observations of Venus and Mercury with the telescope.

The rotation of Venus is an uncertain fact because of the difficulty of finding a particularly stable and well-defined feature on its surface which would enable us to determine the period of rotation. Even by spectroscopic methods it has been found impossible to get definite results, though it is almost certain that its period is not short. Cassini in 1666 and Bianchini in 1726, using the famous telescopes built by Campani, observed some faint spots on its surface which were more or less visible. They were inclined to think that the rotation of Venus was a somewhat slow rotation, of the order of 24 hours. This was discussed later by Schiaparelli in a more complete historical survey of this question.

Schiaparelli began his observations towards the end of 1877. He noted that the surface of Venus showed certain variations and that spots appeared which he was able to observe with a certain regularity and continuity and which he compared with observations made by others. The transient character of the spots is probably due to changes taking place in the atmosphere of the planet. On the other hand, the apparent permanence of the locality in which they occur and the fact that they were often observed by Schiaparelli for several consecutive hours, rules out the possibility of a rapid rotation of the planet of the order of hours or even of a day. It cannot be asserted with certainty that the period of rotation is identical with the period of revolution, because of the transient nature of the spots. Nevertheless, combining his observations with those of others, Schiaparelli arrived at some important conclusions.

The rotation of Venus must be extremely slow, and is such that the position of the spots, relative to the terminator, does not appear to undergo any appreciable changes during a whole month. Observations of a few well-defined spots, lead to the conclusion that the period of rotation of Venus is probably about 224·7 days, that is, a period exactly equal to the sidereal revolution of the planet, around an axis almost at right angles to the plane of its orbit. However, we cannot exclude the possibility that the period might be greater or

Plate 15. Venus in blue light. 200-inch Hale telescope. Mt. Palomar

smaller than this by several months. One thing is certain, the period of rotation is not short, not even of the order of a day.

Schiaparelli also observed the formation of dark and bright spots which appear to reproduce themselves in the same locality, and also small bright well-defined spots, which often appear in pairs, sometimes surrounded by intense dark shadows. These small bright spots occur in various parts of the surface of the planet, especially towards the terminator, and they last only a few days. The planet is surrounded by a dense atmosphere which is almost entirely opaque. It is seen from the Earth as a whitish surface, which shines by the reflection of the light of the Sun, due to the dense vapours which envelop the planet. The spots, which may well depend on the nature and character of the surface of the planet under the atmosphere, do not frequently appear.

The measurement of the radial velocities obtained from the high dispersion spectrograms of the opposite limbs of the planet gives no appreciable shift of the lines due to Doppler effect. Thus we have a good confirmation of the visual observations made by Schiaparelli, and a proof that the velocity of rotation of the planet is certainly too small to be measured spectroscopically. On the other hand, consideration of physics leads one to suppose that a slow rotation would be unlikely, for in this case water vapour would disappear from the regions of the planet facing the Sun and a condensation would occur in the regions in shadow.

Recent investigations carried out by Richardson with the large telescopes at Mt. Wilson have led to very important results. Photographs in ultraviolet light have shown the existence of dark bands on the surface of Venus. Very probably these bands, as in the case of Jupiter and Saturn, are parallel to the equator, and this enables us to determine the equator and hence the direction of the axis of Venus.

The slow rotation of Venus has been confirmed by spectroscopic observations at the limbs of the planet. When the slit of a spectrograph is set in a suitable direction on the disc of the planet, the result obtained shows that the period of rotation is about 14 days. In spite of the difficulty of making these measurements this result can be considered very plausible. A careful examination of the photographs taken in ultraviolet light reveals the existence of some spots which seem to appear in the same region of the planet at an interval of approximately 14 days. Moreover the recent observations of radio emission from the planet show periodic fluctuations about every 13 days. Radio emissions from Venus appear to be similar to those

received from Jupiter and Saturn. It may well be that we are dealing here with electromagnetic manifestations, which develop in the atmosphere of these planets following disturbances similar to those occurring on the Sun or on the Earth.

If the rotation period of Venus were equal to that of its revolution, namely 225 days, conditions would not be conducive to the existence of life, since one half of the planet would be exposed continually to the radiation of the Sun, while the other would be in the shade. On the other hand, a rotation period of 14 days would present a very different situation. On a planet where the Sun and the stars are invisible, the thickness of the layer of clouds could store the heat during seven of our days and quite easily radiate it in the other seven days.

Pettit and Nicholson have found, by using their radiometric measurements, made at Mt. Wilson, that there is a greater amount of radiation from the southern cusp than from the northern cusp of the crescent. This may depend, either on special conditions in those regions of the planet, or on the fact that the rotational poles of Venus did not coincide at that time with the illuminated poles. Moreover, Pettit and Nicholson find that the sunlit surface of the planet reaches a temperature of about 50° C., while the part which is in the shadow has a temperature of —20° C. This is what one would expect if the radiation is emitted from cirrus-like clouds which cover the atmosphere of Venus, so that on the planet there is a nearly uniform temperature, both in the sunlit and in the dark hemisphere.

A phenomenon similar to that observed as earthshine in the case of the Moon is sometimes observed on the hemisphere of Venus not illuminated by the Sun. However, while in the case of the Moon the phenomenon is constant for obvious reasons, on Venus it is of an intermittent and irregular nature. The effect was discovered by Father Riccioli in 1643 and has been observed and studied by Schiaparelli, who finds that it is noticeable when Venus is in the crescent phase, in the interval between inferior conjunction and its greatest elongations, when the illuminated phase of the planet occupies about one to four tenths of its diameter.

We cannot postulate a cause similar to that which gives rise to earthshine in the case of the Moon, because Venus has no satellites and the amount of light Venus receives from the Earth is too small to be perceived; moreover if the ashen light of Venus were due to illumination from the Earth, then the phenomenon should be constant.

As has been suggested by Schiaparelli, there may be two probable explanations. It may be that it is purely a question of contrast against the background of the surrounding sky, if this were illuminated in any way, for example by the zodiacal light or by the solar corona. This would then explain the greater darkness of the unlit disc of Venus compared with the background of the sky. Or else, as seems more probable, the cause of the phenomenon is to be sought in the surface of the planet itself, or in its atmosphere, and it may be that we are dealing with the light of the planet itself.

The fact that the phenomenon of the ashen light is rather rare, and only occurs at irregular intervals, leads us to suppose that there may exist in the atmosphere of Venus electrical phenomena which are similar to those occurring in the terrestrial atmosphere where, besides the polar aurorae, there is always some light present in the night sky. The intensity of this light as well as its variability and composition can nowadays be determined. If something similar to this occurs on Venus, and if the planet rotated rapidly around its axis, which has only a small inclination to its orbit, we ought to observe a maximum intensity and frequency of these supposed luminous effects, principally in the polar regions. The ashen light should therefore be seen in the neighbourhood of the cusps of the bright crescent, but this is in contradiction with observations.

According to Schiaparelli's hypothesis, the solar radiation reaches Venus symmetrically with respect to a line joining its centre to that of the Sun, and thus, either because of its climate or its electromagnetic effects, there ought to be not a thermal equator, but a pole of maximum heat, situated in the subsolar point. On the opposite side, that not illuminated by the Sun, we have a hemisphere with polar temperature. Over this, if the terrestrial analogy is valid, we ought to see the phenomena more or less luminous which could give rise to the ashen light. It has been observed that the ashen light is seen in a zone which surrounds this unlit pole, a fact which has some similarity with the distribution of the polar aurorae on the Earth.

An interesting line of research suggested by Schiaparelli, which it should be possible to follow by means of our modern methods of observations, would be to investigate if there exists a frequency correlation between the occurrence of the ashen light and the solar and corresponding terrestrial activity. The phenomena observed on Earth following solar activity should be observed greatly enhanced on Venus.

Direct photographs of Venus with modern instruments have not

added much to our knowledge (Plate 15). Ross has photographed the planet by enlarging the focal image obtained with the Mt. Wilson telescope, in ultraviolet light (λ 3600 Å.). These photographs reveal many details similar to those observed by Schiaparelli which could be interpreted as cloud formation, while photographs taken in red light and in infrared light do not reveal any detail. We may suppose that the outermost atmospheric layers of Venus are composed of a relatively thin layer of cirrus-like clouds, while the inner layers are appreciably denser and yellowish. The spots are probably atmospheric disturbances, which are bright or dark according to their physical conditions. The bright ones, which are believed to be near the poles, are generally found near the cusps. The dark markings are generally seen as parallel bands to the regions which are believed to be the equatorial regions of the planet. Because these atmospheric disturbances are oriented in the manner described and are subject to rapid changes, Ross believes that the rotation period of the planet is not as long as its revolution period.

The light-curve, which depends on the phase angle of the planet, varies in a manner totally different from that of Mercury and the Moon. At an angle of 120° in the case of Venus, there is an excess of almost one magnitude as compared with Mercury. This would indicate that there must exist a considerable difference in the physical conditions of the reflecting layers of the two planets. It is not possible to represent the light-curve of Venus as a function of the phase angle, according to known laws of illumination, because of the unknown variation, which must arise in the gaseous envelopes of the planet.

If we start from the known dispersion and reflection of light from terrestrial clouds, we can arrive at a law of illumination for an atmosphere like that of Venus. This law is in good agreement with the observations for phase angles which are not too large, if we assume an albedo of 0·6 and a transmission coefficient equal to 0·8.

Lyot carried out some interesting research at the Meudon Observatory, on the polarization of the light of Venus. From these observations he was able to draw the polarization curve for Venus for all its phase angles, as he was able to make his observations even in daylight. This curve, which gives the variations of the proportion of polarized light observed under various conditions, shows that the atmosphere of Venus does not undergo frequent disturbances, as in the case of Mars. The curve is peculiar in that it has two maxima

and a broad minimum, so that it changes sign four times according to its phase angle.

Laboratory experiments performed by Lyot indicated that the polarized light emitted by the planet must be produced by the clouds in its atmosphere, and, in fact, the various inversions of the polarization curve closely resemble that for clouds of liquid globules. The remarkable and uniform brightness of Venus, and the visual observations, confirm the fact that the planet is completely covered by clouds. We are thus unable to have any direct knowledge of the conditions of the surface beneath.

As far as the nature of the liquid globules is concerned, it is unlikely that droplets as large as those found in terrestrial clouds can give rise to the observed polarization curve.

In an attempt to explain this polarization effect, Lyot experimented with droplets of a very opaque colloidal solution having an index of refraction comparable to that of water. The diameter of the droplets was of the order of $2\,\mu$. The existence on Venus of something similar to this is confirmed by the fact that, when the phase angle exceeds 160°, the brightness of the crescent increases instead of decreasing, as would be expected if the light reflected from the planet followed Lambert's law.

The regularity of the variations observed in the polarized light from Venus, shows that the nature of its clouds is practically the same for all latitudes. This appears to be in agreement with the radiometric measurements carried out at Mt. Wilson, according to which the temperature of Venus is very uniform. The differences in the proportion of polarized light from the terminator or from the cusps, as compared with that from the limb, can be explained as being due to the fact that near the inner edge of the luminous crescent the light of the Sun falls solely on the external part of the clouds, and this external part may well differ from that of the deeper layers.

We cannot obtain much information about the composition of the atmosphere of Venus by means of spectroscopic observations, partly because we are dealing with light reflected from a body having a low temperature, and partly because the more intense bands of the gases more likely to be present are to be found in regions of the spectrum which are inaccessible. Weak bands for a few gases are found in the visible region of the spectrum. It is impossible to detect the presence of hydrogen, nitrogen, carbon monoxide, neon, argon since their bands are invisible to us, but we can look for the presence of oxygen, water vapour and carbon dioxide. The first two are, as

is well known, abundant in the terrestrial atmosphere, and give rise to many bands in the visible region of the solar spectrum. These bands would, therefore, be superimposed on those which might be produced in the atmosphere of Venus, and this makes the identification difficult.

St. John and Nicholson at the Mt. Wilson Observatory, using the Snow horizontal telescope combined with a grating spectrograph of high dispersion, were able to prove without doubt that no absorption lines or bands are produced in the atmosphere of Venus. They obtained these results by selecting the times when the velocity of Venus relative to that of the Earth was sufficient to bring about a complete separation of the corresponding lines produced in the two atmospheres. The observations were carried out when the velocity of Venus relative to the Earth was $-7{\cdot}9$ miles/sec., which corresponds to a Doppler shift of 0·268 Å towards the violet. This is more than sufficient, because of the high dispersion used to separate completely the lines due to Venus from those due to our own atmosphere. The lines which were observed in particular were those due to water vapour near λ 5900 Å, and the bands of oxygen in the red region of the spectrum.

From observations we can conclude that in the layers of the atmosphere of the planet which are crossed by the rays of the Sun, there cannot be more than the equivalent of a depth of about 3 feet of oxygen, and less than a fraction of an inch of precipitated water vapour, that is to say, less than a thousandth part of that existing in our own atmosphere. These investigations, which replace the older ones carried out by more primitive means, do not leave much room for doubt, but they do not prove conclusively the absence of water vapour and oxygen in the atmosphere of Venus. They rather suggest that water vapour and oxygen are not present in its atmosphere, at least as far as the limit reached by the rays of the Sun.

Recently, Adams and Dunham at the Mt. Wilson Observatory, by studying the intense bands which are found in the infrared region of the spectrum, were able to confirm the absence of both oxygen and water vapour in that layer of the atmosphere of Venus which we are able to investigate. For this research they used a spectrograph placed at the end of the polar axis of the 100-inch reflector. The dispersive element of the spectrograph was a grating which gave a dispersion of 5·6 Å/mm. The spectrograms obtained revealed the existence of two bands with heads at λ 7820 Å and λ 7883 Å and another at λ 8689 Å. These are sharply defined at their violet end but

fade away towards the red, conforming to the general characteristics of oxygen bands. The bands observed are due to carbon dioxide, as was established by the theory of band spectra and by experiments in the laboratory. Using the same spectrograph, Dunham was able to reproduce these bands in the laboratory and by a series of experiments was able to conclude that the total amount of carbon dioxide present in the visible surface of Venus was at least 1·9 miles thick at a pressure of one atmosphere, but it is possible that the total amount over the whole solid crust of the planet may be considerably greater. By comparison we note that the whole of the atmosphere of the Earth under the same conditions would be 5 miles thick, of which a thickness of 1·2 miles would be oxygen. Carbon dioxide is very scarce, and calculations show that the corresponding layer would be only about 33 feet thick, at a pressure of one atmosphere.

The spectroscopic results lead to various speculations, such as have been discussed by Russell. We know that on Earth the carbon dioxide is continually absorbed by plants, which then emit oxygen. In a planet void of life we must therefore expect to find carbon dioxide and little or no oxygen, which may well be the conditions obtaining on Venus. It is more difficult to account for the absence of water vapour on Venus since this planet is so much like the Earth in size and mass. It is possible that water vapour cannot be detected with present spectroscopic means, or else that the whitish clouds which cover the surface of the planet are composed of a certain chemical combination of carbon, hydrogen and oxygen under the action of solar radiation.

It might be thought possible that Venus, which has dimensions comparable with those of the Earth and which is not as close to the Sun as Mercury, might be able to support life. However, from what has already been said, it is more probable that such conditions do not exist on the planet. According to Spencer Jones, the planet is deserted; strong winds blow permanently over its surface, and yellowish dust, like sand, is carried to great heights in its intensely hot atmosphere. There are no high mountain ranges, nor vegetation, since the sands, probably of volcanic origin, which are carried by the strong winds, have levelled the surface of the planet.

Venus appears to have no satellites, at least so far none has been discovered. If a satellite existed very close to the planet it would be difficult to discover it either because of the great brightness of the planet or because of its proximity to the Sun.

At inferior conjunction, the planet may cross the disc of the Sun

from east to west, and it appears then as a dark spot on the solar disc which can be seen with the naked eye. Central transits last about eight hours, and observations of these are important for the determination of the solar parallax. Expeditions have been made entirely for this purpose by various nations to observe the transits of December 8, 1874, and of December 6, 1882. The next transit will take place on June 7, 2004, and June 5, 2012. At the time of transits, when the disc of Venus enters or leaves that of the Sun, observations confirm the existence of an atmosphere around the planet.

The advent of new instruments in the form of stratoscopes, rockets, space probes and artificial satellites, has given to the astronomer new means of investigating complicated problems and in particular the hope of obtaining a better understanding of the conditions prevailing on the planets and in the solar system as a whole.

One of the greatest achievements in this field has been the journey of Mariner 2 towards Venus, which has given us a wealth of information about this planet.

Mariner 2 was launched on August 27, 1962, from Cape Kennedy in Florida, and after 109 days, on December 14, 1962, reached the neighbourhood of Venus. The orbit of Mariner 2 was chosen so that it should approach Venus, but at the same time remain at such a distance so as not to fall under the complete control of the gravitational field of the planet. At the time of the nearest approach, Mariner 2 was 21,598 miles from Venus. While travelling in space, it sent back to Earth important information on the conditions which it met. About 13 million words were received during this period.

Instruments were installed in the space-craft in order to obtain information on some of the most important questions the astronomers had asked themselves for centuries. Mariner 2 was equipped with a microwave radiometer in order to determine the temperature of the surface of Venus and record details concerning its atmosphere. An infrared radiometer was included to give information about the structure of the clouds and the distribution of temperature at various cloud altitudes. A question which was considered to be very important was whether a magnetic field existed on the planet, and for this purpose a magnetometer was carried by Mariner 2.

It was felt that in the journey to Venus important data could also be obtained about interplanetary space, so that in addition to the other instruments, Mariner 2 was also equipped to observe and

measure high-energy cosmic radiation, the intensity and speed of the 'solar wind', and to determine whether in the neighbourhood of Venus there was evidence of the existence of belts similar to the Van Allen belts which are formed around the Earth.

It will certainly be some time before all the data received from Mariner 2 can be fully studied and interpreted; however, already considerable information is available from the preliminary results. These can be summarized as follows:

1. The rotation period of Venus is very slow and is of the order of 230 days, and the rotation may be opposite to that of the Earth.

2. At the distance of 21,598 miles from the planet no magnetic field was detected and there was no evidence of high-energy particles being trapped around Venus.

3. The thickness of the clouds is of 15 miles, with the cloud base at 45 miles above the surface of the planet.

4. The surface temperature of Venus, as determined by the microwave radiometer, appears to be approximately 427° C., and the albedo is equivalent to that of dust and sand.

5. The heavy, dense atmosphere produces a surface pressure which is about twenty times that we have on the surface of the Earth.

The most important results concerning interplanetary space are those referring to cosmic dust and solar wind. Observations show that the cosmic dust density in space, between the Earth and Venus, is about ten thousand times lower than that prevailing in the immediate neighbourhood of the Earth. The solar wind or plasma, streaming continually out of the Sun, travels through space with a velocity ranging from 200 to 500 miles per second.

If we combine these observations with those already obtained from the Earth, we reach the conclusion that the average temperature of Venus is too high to support life even remotely similar to that on Earth, and that the sky is perpetually obscured by a thick layer of clouds in which carbon dioxide predominates.

The question of the length of the period of rotation of Venus is still unsolved, in the sense that it has not been possible to determine it accurately. In recent years radar has been used in an attempt to determine not only the period and direction of rotation, but also the conditions of the surface of the planet. From the study of the signals bounced back from Venus, it was possible to find that the planet is rotating in the opposite direction to the rotation of the Earth and that the period of rotation is a little longer than that of revolution.

If these data are confirmed, the possibility of existence of life on Venus becomes even less probable.

Venus has no satellite and therefore the determination of its mass could only be obtained by the study of the perturbations of the motion of Mercury. Mariner 2, however, acting as a satellite of Venus has made it possible to determine accurately the mass of the planet. This is found to be 0·815 times that of the Earth. The mass was obtained by studying the perturbations of the space-craft when passing near Venus.

Finally the data from Mariner 2 enabled astronomers to determine very accurately the distance between the Earth and the Sun, a distance which is of such importance to astronomers. This distance is 92,956,200 $\pm$ 300 miles.

Perhaps before long it will be possible for the astronomers to discover most of the secrets of Venus, which is one of the most mysterious of the planets of the solar system.

It will be noticed that the question of the rotation of Venus remains still a mystery. Many estimates have been made in the last three hundred years, adopting various methods. Perhaps it will be useful to summarize them briefly here.

The earliest estimates were made by visual observations of bright and dark shadings on the disc of Venus. These features are not well defined and therefore the results do not appear to be very consistent.

In 1666 Cassini gave a value of 23 hours 21 minutes and similar results were obtained in the early part of the nineteenth century by other observers. Schiaparelli suggested that the period was very long (see page 240).

In the twentieth century a solution of the problem was attempted by spectroscopic means. The difficulty here appeared to lie in the determination of the tilt of the axis of Venus. Belopolsky in 1911 thought he detected a Doppler effect and estimated the rotation of Venus to be between 24 and 35 hours. A series of photographs in ultraviolet light obtained by Ross in 1927, suggested a rotation of about 30 days (see page 244). Richardson (see page 241) considered that the true value must lie between $3\frac{1}{2}$ and 46 days. In more recent years radioastronomy has been used in the hope of obtaining a solution to this problem.

The question of the period of rotation of Venus remains still unsolved and in recent years results have been obtained which are extremely contradictory, as it appears from the discussion in this chapter.

CHAPTER V

The Earth and the Moon

The characteristics of the Earth, as a member of the solar system, are well known. We shall, therefore, give here only a brief reminder of some of the main data.

The Earth is at a distance of approximately 93 million miles from the Sun, around which it revolves with a sidereal period of 365·2564 mean solar days and with a mean orbital velocity of 18·5 miles/sec. The eccentricity of the orbit is 0·017, while the mean diameter of the Earth is 7,913 miles. Its mass and volume are, respectively, 331,950 and 1,300,000 times smaller than those of the Sun. The specific gravity of the Earth is 5·52 and the period of rotation on its own axis, expressed in mean solar time, is 23 hours 56 minutes and 4·09 seconds. The mean inclination of the equator to the plane of the ecliptic is 23° 26′ 49″ (1942) while its oblateness is 1/296. The apparent magnitude of the Earth, as seen from the Sun, is calculated to be $-3^{m}{\cdot}5$. The albedo, which can be determined by comparing the brightness of the earthshine with that of the lunar crescent illuminated by the Sun, is 0·45, a value which is between those of planets having clouds and planets without clouds. The observations also show that the earthshine has greater radiation in the blue region of the spectrum, than the part of the Moon illuminated by the Sun. This is not surprising since the light reflected by the Earth is mostly reflected by its atmosphere.

It is interesting to speculate on the appearance of the Earth as seen from the other planets, since this will also help us when we compare the Earth with them. A large part of the Earth would appear covered by clouds and this would reflect much more light than the parts without clouds. Except for the areas of deserts, it will be extremely rare to see parts of the Earth free from clouds and therefore very little of the features of the surface of the Earth would be

visible. The reflection of the Sun by the oceans and by the snowy regions must be very bright, while the deserts, which have no vegetation, would appear of a reddish or yellowish colour. The large forests of the Earth would appear to be of a dull blue colour, since the greater part of the reflected light is reflected by the atmosphere above these regions, while the cultivated regions and grassland would be of a greenish colour. Seasonal changes ought to be easily detectable. Apart from any variation in the amount of cloud cover, the advance and retreat of the winter snow, as well as the variation from green to brown in the cultivated regions of the Earth, ought to be visible.

It would be reasonable to think that the Earth is the only planet of which we can explore the interior. However, the technical difficulties are such that we can probe the crust only to a depth which is less than one thousandth of the terrestrial radius. Nevertheless by indirect means, such as the study of the manner in which seismic waves travel through the earth, the study of meteorites, the knowledge of the average density of the Earth, astronomical and geodetic data, it has been possible to put forward certain acceptable hypotheses on the constitution of the interior of the Earth.

It has been suggested that the interior consists of a molten mass of material at a very high temperature, enclosed in a solid envelope of cooled material. This hypothesis was put forward when it was found that the temperature increases by about 1° F. for every 50 feet of depth below a zone where the temperature is constant. From seismic observations it appears that the interior of the Earth behaves as a solid, although a certain amount of viscosity is present. It is certain that the interior of the Earth is hot, but we do not know the temperature. Probably this increases from the surface towards the centre, but the rate of increase is known only for a relatively short distance in depth.

From what we have already said about the Earth's interior (see p. 221) we can state that the propagation of the seismic waves (fig. 36) shows that there exists a considerable discontinuity in the behaviour of the matter which forms the terrestrial nucleus at a depth ranging from 1,864 miles to 2,175 miles. We must assume that the physical state of matter must change at this depth, and since we cannot find out what happens to matter subjected to a pressure of 500 thousand atmospheres, which is the actual pressure existing at that depth, we must rely on hypotheses. If we assume a progressive increase of density from the surface to the centre of the Earth, we can draw a diagram (fig. 37) based on the way seismic waves travel. The central

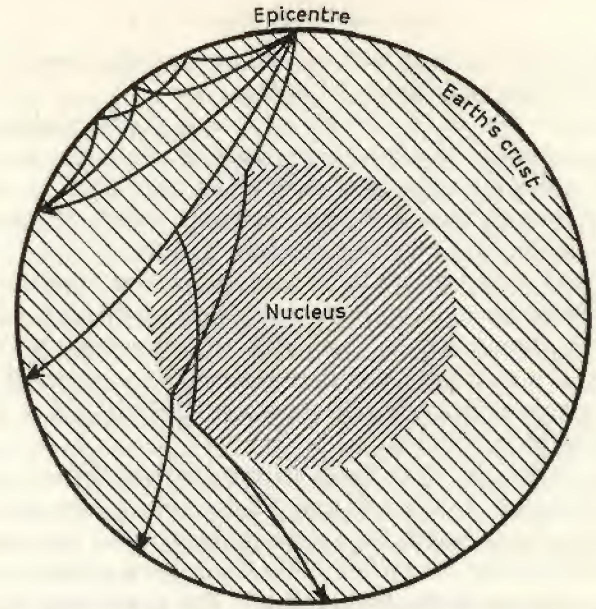


FIG. 36. Propagation of seismic waves in the interior of the Earth. (Rudaux and Vaucouleurs.)

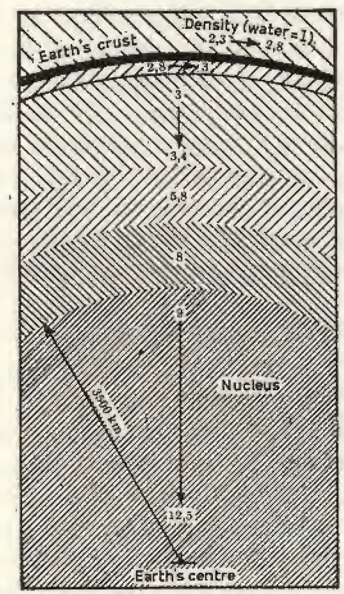


FIG. 37. Probable density of the various layers of the Earth's interior. (Rudaux and Vaucouleurs.)

nucleus would then have a density which increases from 9 to 12·5 and consists mainly of iron and nickel.

The upper part of the Earth's crust, to a depth of about 93 to 124 miles, consists mainly of compounds of aluminium and silicon (Si, Al), hence the name 'Sial'. Below this, to a depth of approximately 930 miles, there is a layer composed mainly of silicon and magnesium (Si, Ma) which is known as 'Sima'.

The Earth is surrounded by an atmosphere which permits animal and vegetable life to exist. In the immediate neighbourhood of the crust, this atmosphere is composed of approximately 78% of nitrogen, 21% of oxygen, and the rest consists of very small quantities of argon, carbon dioxide, hydrogen, helium and a variable quantity of water vapour.

From the surface of the Earth up to a distance where the density of the atmosphere is extremely low, the atmosphere is usually divided into various layers which have given characteristics. The first layer, which extends from the surface of the Earth up to a height of about 7 miles, is known as the 'troposphere'. This is the layer where all the 'weather' phenomena take place and where almost all the water vapour of the atmosphere is to be found. Following this there is a layer of ozone of a variable thickness and height. The 'stratosphere', which is a homogeneous layer with an almost constant temperature, extends above the ozone up to a height of 30 miles. Beyond the stratosphere we find the 'ionosphere', which was discovered after the early experiments in radio communication. Finally, higher than the ionosphere, we have the region where the aurora displays take place, the meteors burn out and where the primary cosmic rays arrive. These primary rays are endowed with very great energy and in colliding with the nuclei of oxygen and nitrogen, break them up and produce the elementary particles which reach the surface of the Earth.

The Earth, as a whole, has a hardness comparable to that of steel and behaves like a magnet. Since, generally speaking, the rocks of the crust are not very magnetic, it is thought that the terrestrial magnetism may be due to the composition and property of the material of its interior. We have already discussed the probable constitution of the crust and interior of the Earth as well as the analogies that can be found when we compare them with those of the Sun and meteorites. These analogies indicate that the Earth was born of the Sun, and although it has reached a certain stability, both externally and internally, it is not free from slow variations, which

show themselves either in the length of the day or in the position of the poles of the Earth, that is to say, the position of the rotation axis in the interior of its mass.

Until recently the duration of the terrestrial rotation had been assumed to be constant and therefore was taken as a basis for the measurement of time. In recent years, however, its absolute constancy has been doubted. It now seems that variations, both regular and irregular, do exist. The regular variations produce a progressive slowing-down of the terrestrial rotation and are probably due to the braking action of tides. The irregular variations have been attributed to the possible variations in both the distribution and the volume of the terrestrial mass. These variations are confirmed by the movement of the terrestrial poles, a movement which has been observed and accurately determined in the last fifty years, at special international stations distributed over the surface of the Earth. The observations show that this movement, although very small, has a regular and an irregular component.

On the Earth we can also observe the possible cosmic influences to which it is subjected and by analogy, we can deduce the order of such influences on other planets. The most important phenomenon is that of the tides. This, as is well known, is produced by the combined attraction of the Moon and the Sun on the liquid masses. Modern and very sensitive instruments have shown that the attraction is also effective, in a very small measure, on the solid crust. Because the Moon is much nearer to us, its action predominates and therefore the periodicity of the tides reflects the lunar cycle.

The planets have an effect on the orbit of the Earth. Its elliptical motion around the Sun is perturbed by the planets, so that the centre of its orbit describes in space a very complicated path, in the course of time. There do not seem to be perturbations of any other type.

We now have to consider the effect of the Sun on the Earth. There are several ways in which the Sun exerts a direct influence on the Earth. By continuous measurements of the solar radiation and study of the various phenomena shown by the Sun during its eleven-year cycle, it is hoped that a better understanding of its influence will be reached. The 'solar constant' has been measured regularly in many parts of the Earth. These measurements indicate the existence of very small variations, which may conceivably have a certain influence on terrestrial meteorology. However, so far it has not been possible to establish any definite relationship. On the other hand, for some time now, it has been possible to show the existence of a relationship

between the solar radiation and the variable activity of the Sun on one hand, and the terrestrial magnetism and conditions of the ionosphere on the other. The variations and perturbations of the terrestrial magnetism follow very closely the activity of the Sun and its storms. These effects are also present in the ionosphere, which is responsible for the reflection and refraction of radio waves.

Let us now consider the Moon, which is our nearest neighbour in space and a satellite of the Earth. Its mean distance from us is 238,857 miles. The Moon revolves around the Earth in an orbit which has an eccentricity of 0·05. Its sidereal period is 27 days 7 hours 43 minutes, and this is also the period of rotation around its axis. As a result of this the Moon presents to us always the same side. The inclination of its equator to its orbital plane is 6° 41′ and the orbit is almost circular. The mean apparent diameter of the lunar disc is 31′ 5″ and its actual diameter is 2,160 miles. The mass is $\frac{1}{82}$ of that of the Earth and its specific gravity is 3·33. At opposition its magnitude is $-12^{m}\cdot55$. The Moon reflects only 7% of the light it receives from the Sun, or in other words, its albedo is 0·07. The rest of the light of the Sun is absorbed by the lunar surface and converted into heat. The albedo is comparable to that of dark rocks, like the volcanic rocks (Plate 16).

The Moon has no atmosphere, therefore the appearance of the hemisphere which is visible is unchangeable and distinct. Many of the details of the surface of our satellite are well known to us, since it can be studied in detail and can be photographed with powerful instruments. The height of its mountains and the depth of its valleys have been measured and the geological nature of its soil has also been studied.

The temperature of the lunar surface is 100° C., and this drops to about −100° C. immediately after the setting of the Sun. The results of the analysis of absorption and radiation of the heat under these particular conditions can be compared with experiments in the laboratory. These experiments have shown that the considerable jump in temperature must be due to a layer of a material like pumice-stone a few inches thick. A considerable part of the energy of the incident sunlight penetrates the layer and heats it. The surface heated in its turn will radiate the absorbed energy into space in the form of heat, 'planetary heat'. This heat has been measured by Pettit by means of a thermocouple, and he found that the quantity of energy radiated is approximately proportional to that received by the surface

Plate 16. The Moon at first quarter (Moore and Chappell)

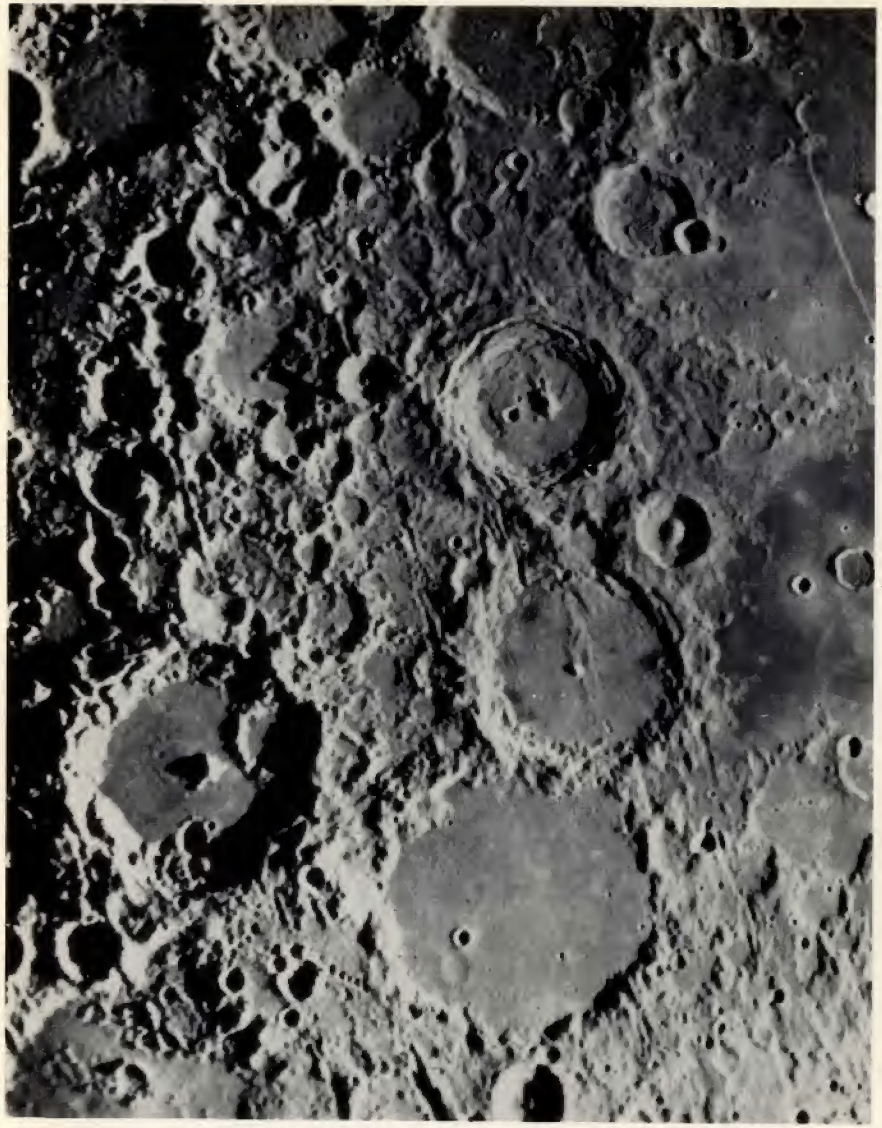


Plate 17. Portion of the Moon at last quarter, from Ptolemaeus to Tycho

Plate 18. A photograph taken by Zond 3 of the other side of the Moon and showing some features visible from the Earth under favourable libration. Reproduced by courtesy of the Novosti Press Agency (A.P.N.)

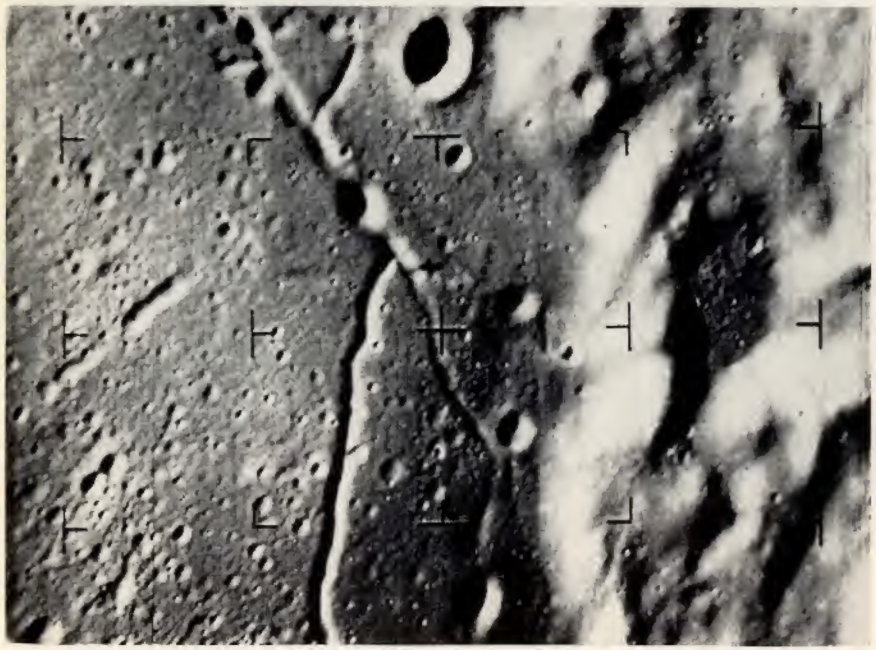


Plate 19. Photographs taken by Ranger 9. (*above*) photograph taken at 775 miles from the surface of the Moon. The crater Alphonsus is on the left. (*below*) photograph taken at 115 miles from the surface of the Moon. Note on the left the crater Alphonsus. Compare these photographs with Plate 17 taken from the Earth and showing the crater Alphonsus right of centre. Photographs reproduced by courtesy of U.S.I.S.

of the Moon. This shows that the Moon absorbs only a very small amount of heat.

Investigations have been carried out on the trajectories of materials erupted by the lunar volcanoes. These trajectories appear to be from 20 to 25 times longer than those of the materials erupted on the Earth with the same initial velocity and the same angle of elevation. The rays, which appear to radiate in all directions from the greater lunar craters, extend up to 1,550 miles. The conclusion reached from these studies is that the material erupted has fallen far from the centre of eruption, and that the craters have not filled in, so that they remain deeper with reference to the nearby regions. These rays reflect and diffuse the light more intensely than the lunar surface on which they are superimposed, and therefore it is suggested that they might consist of bands of fine dust or ash carried by jets of incandescent gases, and deposited along their path.

Some of the slopes of characteristic lunar formations have been measured on photographs taken with the 100-inch reflector at Mt. Wilson under various conditions of illumination. These measurements, together with stereoscopic observations, make possible a very accurate study of the physical 'geography' of the Moon (Plate 17).

Lyot's observations of the polarization of the light of the Moon, show that at the first and last quarter the polarization reaches a maximum and that the plane of polarization is parallel to the plane passing through the Sun, as had already been discovered by Arago. This maximum reaches 6·6% for the waxing Moon and 8·8% for the waning Moon. This difference in the two maxima is due to the fact that the 'maria' cover an area twice as big at the last quarter as at the first. The sudden decrease in the polarization, which takes place in the last quarter, coincides with the disappearance at the terminator of the dark regions of Mare Nubium and Mare Imbrium. Towards new Moon the polarization decreases and the two branches of the curve approach each other rapidly. Two days before full Moon, at a phase angle of about 23°, the polarization becomes zero and appears again a few hours later in a perpendicular plane. Lyot and Wright have shown that volcanic ash and pumice-stone, having a high content of silicon, have general characteristics which are very similar to those shown by the lunar surface. Volcanic ash is grey, sometimes brown or bluish, and is reminiscent of the faint colouring detected occasionally on the maria. Moreover the reflecting power of the above materials is of the same order as that of the dark and light lunar regions. Finally the lunar surface, illuminated obliquely,

diffuses more light in the direction towards the Sun than in the opposite direction. Such an effect is observed in surfaces covered by dust and in particular covered by volcanic ash.

The above analogies lead us to conclude that the Moon must be covered by dust, which has a composition very similar to that of terrestrial volcanic ash. Probably this dust is scattered in a very thin layer covering the lunar surface which consists of lava.

The shape and characteristics of some of the craters and of the many craterlets which are observed on the lunar surface have given rise to the theory, put forward in 1949 by Baldwin, that the craters are produced by meteoric impact. Measurements show that some craters are not very deep and that their edge is only a little higher than the general level of the neighbourhood. These facts do not agree too well with the explanation of the volcanic origin of the craters.

On the Earth we have a good example of a crater produced by a meteorite. The Arizona Meteor Crater (U.S.A.) has a diameter of just over half a mile and has been made in the solid rock. It has a slight slope towards the outside, uneven walls in the interior and is smooth and shallow at the bottom. The meteorite which fell on the Earth long ago and produced that crater was never found intact, but only in the form of small metallic fragments, scattered within the crater or in its neighbourhood. Calculations suggest that the meteorite, composed of iron and nickel, which produced this crater must have had a diameter of about 49 feet. In the impact, either the meteorite broke up, or possibly it embedded itself in the ground so deeply, that so far it has not been possible to find it. The evidence of the Arizona Crater would suggest that the lunar craters, with diameters between 20 and 60 miles, must have been produced by meteorites having diameters ranging from 220 yards to 550 yards or even more, possibly reaching the dimension of the asteroids which revolve around the Sun in orbits between Mars and Jupiter.

It can be said that 'selenography' started when Galileo first pointed his telescope to the Moon. From what we have already said we can see that, although the Moon is our nearest neighbour in space, there are still many questions which remain unsolved, such as the constitution of its surface and the formation of craters.

In recent years there has been, among astronomers, a considerable renewal of interest in the lunar problems. Developments in electronics and in the space probes have opened new fields of studies. Teams of astronomers in many countries have developed new methods and

new instruments in an effort to understand better the conditions prevailing on the Moon. Space-craft have been sent into the neighbourhood of the Moon to obtain data and photographs which were then transmitted back to Earth. It has already been possible to crash-land lunar probes on the Moon and plans are in hand now to follow up these surveys by soft-landing instruments on the surface of the Moon. It is hoped that this project (the 'Surveyor' planned by the U.S.A.) will enable us to obtain definite information not only about the condition of the Moon's surface but also about the constitution of its crust and even about some of the layers below.

Already great progress has been made, and the wealth of data obtained in recent years by means of space-craft has been increasing steadily.

On account of the fact that the rotation period of the Moon is the same as its period of revolution around the Earth, man has never been able to see the other side of the Moon. A lunar probe, launched from Russia and known as Lunik 3, was set on an orbit which would pass close to the other side of the Moon, and on October 7, 1959, photographs of the invisible side of the Moon were received on Earth. The photographs were taken from a distance of about 40,000 miles from the Moon. These photographs do not show great details. It must be remembered, however, that they were taken when the light of the Sun was falling almost at right angles to the surface of the Moon and therefore there is very little shadow, and this prevents the clear identification of mountain ranges and the detection of the depth of craters. The result is a rather 'flat' photograph similar to those obtained from the Earth at the time of full Moon. On July 18th 1965 another Russian spacecraft named Zond 3 was launched into space in an orbit which passed behind the Moon. Zond 3 was equipped with both photographic and spectrographic equipment and took 25 photographs of the surface of the Moon at a distance of about 6,000 miles. It also obtained spectra in the region λ 4000 Å and λ 1900 Å and all this information was relayed back to Earth. The camera used for this purpose had a focal ratio f/8.

The Zond 3 photographs confirmed the results already obtained by Lunik 3 and show more than 1,000 craters with diameters ranging from about 2 miles to 60 miles.

These new pictures are extremely interesting because about a third of the area covered by them shows features which are visible from the Earth under favourable libration (Plate 18) and this acts as a link between the visible and invisible parts of the Moon.

From these photographs it appears that, as was expected, the other side of the Moon does not show any very different features from those well known to us, namely maria and craters. The distribution of these features is different in the two sides of the Moon, but this is not really surprising since, after all, this is also the case on our own Earth, where the continents and oceans are not symmetrically distributed in the two hemispheres.

In 1964 and in 1965 three American lunar probes, Ranger 7, 8 and 9 were crash-landed on the Moon, and as they were hurtling towards the surface they took close-up photographs of the visible side of the Moon (Plate 19). Altogether these three spacecraft have sent back 17,700 pictures of a very high quality, and as the point of impact in each case was a different one, a fairly large area of the Moon has now been photographed from a very close range. In the case of Ranger 8 and 9 the last photographs were taken from a height of a few thousand feet from the lunar surface, less than half a second before impact. They show a great number of craters and microcraters some as small as 2½ feet in diameter.

Scientists are already at work on the great wealth of information that these photographs provide, but it will be some time before we understand the full significance of all the data which have been obtained. It is hoped that these photographs will be able to tell us whether the surface of the Moon is covered by a deep layer of dust or not. Preliminary results obtained from these photographs have not yet given a definite answer to this question. It has been suggested that on the Moon there may be sedimentary processes which lead to particles becoming joined together by a kind of vacuum welding as well as by compression. The size and nature of the very small craters, which also appear to be relatively newer craters and which are shown in photographs taken by the Rangers, suggest a surface which does not present a great resistance to impact. This would appear to indicate that the surface of the Moon is not covered by a layer of dust, but rather consists of a kind of foam lava which is very brittle.

It must not be thought, however, that astronomers are relying only on spacecraft to learn more about the condition of the surface of the Moon. Extensive programmes of lunar research have been planned in many centres. New photographic techniques have been developed so as to enable large-scale lunar maps to be prepared, showing a wealth of details.

From terrestrial observatories the light of the Moon is being studied, to determine its polarization, its variation of intensity and

possibly of colour, the effects of luminescence at different points of the surface, and to study many other questions which are of great interest.

All these investigations, which are complementary to the observations and photographs obtained by space-craft, will, perhaps before long, give the answer to many questions the astronomers have been asking themselves since the days of Galileo.

CHAPTER VI

Mars and Its Satellites

Among the members of the solar system, Mars is without any doubt the planet most studied, probably because of the appearance of its surface and because of the phenomena occurring on the planet which may be said to have some analogy with our Earth.

Mars is on average at a distance of 141·5 million miles from the Sun. Its sidereal period is 686·98 mean solar days and its average orbital velocity is 15 miles/sec. The eccentricity of its orbit is 0·093 and the inclination of its orbit to the ecliptic is 1°·9. The other important data for Mars are: diameter 4,216 miles, mass 0·11 that of the Earth, volume 0·15 that of the Earth, while its specific gravity is 4.

Because of the high eccentricity of its orbit, the apparent angular diameter of Mars varies from 3″·5 to 25″·1. At its mean opposition its magnitude is $-1^{m}{\cdot}85$. The period of rotation of Mars is 24 hours 37 minutes 22·58 seconds. The albedo of the planet is 0·15, which is more than twice that of the Moon or Mercury and comparable to that of rocks of a rather dark hue.

Since the orbit of Mars is external to that of the Earth, the planet does not show phases like Mercury and Venus, although when in quadrature the disc appears gibbous like the Moon three days after full Moon.

According to recent determinations the inclination of the equator of the planet to the plane of its orbit is 25° 10′, which is very similar to the corresponding value for the Earth, so that the seasons on Mars are similar to those of the Earth.

The opposition of Mars may occur near its perihelion or its aphelion. In the first case its distance from the Earth is only 34·5 million miles, while in the second it is 63 million miles. Opposition takes place every 2 years and 49 days, but the most favourable

oppositions for observation of the planet are those which occur at perihelion, where the orbits of Mars and Earth are at their closest, which takes place every 15 or 17 years. In recent years there have been the notable oppositions of 1924, 1939 and 1956, the last one, like that of 1924, occurring when Mars was only 0·38 A.U. from the Earth.

The Martian seasons have unequal lengths because of the form of the orbit and on account of the velocity of the planet. The longest season is spring, while the shortest is the autumn. The northern hemisphere is exposed longer to the hot season, with consequences to its meteorological conditions which are visible to us.

The appearance of the surface of Mars has been studied, drawn and classified by many observers and in particular by Schiaparelli. Detailed maps have been made of the surface of the planet and many features have been named, bearing in mind any terrestrial analogies. For instance the bluish patches have been called 'seas', the yellowish ones 'land', and the dark streaks or lines were named by Father Secchi 'canali', translated into English as 'canals'. Schiaparelli was careful to point out that all these names did not necessarily have a physical reality.

Careful and patient studies of the features of the surface of Mars have not yet given any clear indication of their nature. This is mainly due to the fact that even the largest telescope available and the highest magnification do not enable us to study the features of the planetary surface closely or to separate any details. The image of the planet given by telescopes is always far too small to enable us to make any detailed study, and neither photography nor spectroscopic investigations have contributed very much to the interpretation of our observations. Nevertheless it is true to say that since the pioneering work done by Schiaparelli, some new and important theories have been put forward. Thus by combining the results of both visual and photographic observations, it has been possible to make some suggestions on the possible configuration of the planet, irrespective of the difficulties due to imperfect images and insufficient resolution of the various parts of the markings and of other peculiarities.

Careful observations have shown that the light and dark patches of various colour and hue, which can be detected on Mars, are generally always the same and present themselves to the observer in sequence, during the rotation of the planet. The identification of the markings with continents, mountain ranges, lakes or rivers similar

to those existing on our Earth, is only possible if we assume that Mars is not very different from our own planet. Moreover the existence on Mars of the polar caps, which are clearly visible, and which are covered by ice and then thaw periodically following the cycle of the Martian season, may be taken as a confirmation of the above hypothesis.

The famous 'canals' which, according to modern observations, can be resolved into a number of spots of varying extension and geometrical form, may be compared to some similar features on our own globe, such as the Mediterranean Sea, the Red Sea, the Caspian Sea, Baffin Bay or some of the land formations of groups of islands such as the West Indies, East Indies and New Zealand.

The variation of both the definition and the colour of the various configurations could be explained by the presence of clouds, which, as on Earth, could cover some regions of the planet, apart from any variation due to the angle of incidence of the sunlight. However, the analogy between Mars and Earth should not be carried too far since any conditions of life on Mars would be very different from those prevailing on Earth because of the distance of Mars from the Sun. This is also confirmed by spectroscopic observations.

If we study the observations and the description of the details of the Martian surface given to us by observers such as Antoniadi and Maggini, we can understand better the appearance and the changes occurring on the surface of Mars. For instance, one of the most peculiar regions is that called 'Thaumasia Felix' or 'Land of Wonders' as Schiaparelli rightly called it and which is located at 90° areographic longitude (Plates 20, 21). This region is a patch of an orangy colour, slightly oval in shape, covering approximately 45° areographic. In the middle of this patch there is an almost circular, dark spot called 'Solis Lacus'. This central dark spot, which according to Maggini becomes a cluster of small nuclei at the time of the favourable opposition, is joined to the edges of the 'Thaumasia Felix' by arcs and linear features (canals) which appear very regular. Under excellent seeing conditions, the various parts of the region have very different colouring. The southerly half is much darker and in it many details of 'Solis Lacus' can be detected. 'Solis Lacus' seems to be divided into two parts crossed by a 'bridge' of a lighter colour, and the lines joining it to the edge of the region can be seen. During the 1924 opposition, Maggini was able to detect that the geometrical forms described above in this remarkable Martian configuration, showed a wealth

of detail. Towards the middle of August 1924, the 'Solis Lacus', which had reached the central meridian of Mars, became lighter while the background was of a dark grey colour, as if some light fog had spread like a veil over the whole region. Suddenly, the 'Solis Lacus' seemed to disappear and the only part still visible was the southern edge of 'Thaumasia Felix', while the whole region appeared studded with small dark nuclei irregularly distributed. Such changes are due, very probably, to condensations which occur in the planet's atmosphere and to our inability to resolve the observed details, which are visible only in conditions of exceptionally good seeing and when Mars is free from clouds.

Antoniadi reached the conclusion that as far as the 'canals' were concerned, about 70% of them were irregular dark bands more or less uninterrupted and studded with smallish spots of various size and appearance; 21% were the irregular edges of diffuse grey spots and 9% were composed of isolated, complex nuclei.

Real changes undergone by some of the features of the Martian surface have been duly noted by various observers, but naturally it is difficult to assert which changes are real and which are due to some of the causes mentioned above.

Maggini in 1928 detected a notable change in the region of 'Noachis'. South of 'Sinus Sabaeus', which is the darkest feature of the Martian surface, he observed a band equally dark which crossed obliquely the lighter region of 'Noachis'. The band was of a deep blue-violet colour contrasting with the brownish red of 'Sinus Sabaeus'. This appearance remained unchanged for several months and was confirmed by other observers.

Changes which may be due to seasonal effects have also been often observed, particularly in the large dark marking known as 'Syrtis Major' and in 'Pandorae Fretum'. From the observations available it seems that the appearance of these regions depends upon the position of Mars in its orbit around the Sun. 'Pandorae Fretum' is generally dark in colour from the spring equinox to the summer solstice and particularly at perihelion; while it becomes very pale and almost invisible after the summer solstice. These phenomena may be due either to real physical changes on the planet or, as suggested by Cerulli, they may depend on the changes in the illumination of the various regions, produced by the rotation and by the phases of the planet itself.

According to Antoniadi, changes in colour occur sometimes in advance or sometimes late with respect to the Martian seasons, and

are of very short duration. Thus 'Syrtis Major', which is normally bluish-grey or greenish, becomes brown when the planet occupies certain positions with respect to the Sun. Maggini observed the best colouring in 'Mare Cimmerium' and in 'Mare Sirenum'. The first was bluish grey with the exception of the north side which was red, while the second showed several colours, greenish blue, red and brown. This suggested that probably 'Mare Sirenum' consisted of several spots, each one behaving in a different way.

The changes which occur in the polar caps are obvious (Plate 22). A telescope of small aperture will show these changes and enable an observer to follow the interesting transformations. The brightness of the polar caps shows that the atmosphere of Mars is very tenuous, and this is also proved by spectroscopic observations. In fact, as a further proof of this, if the atmosphere were dense we would have a considerable absorption at the edge of the disc where the polar caps are, and this effect is not observed.

The north pole of Mars can be observed at the opposition near aphelion, namely at the more unfavourable oppositions. The south pole, on the other hand, is visible at the time of oppositions taking place near perihelion and therefore it can be better studied in all its details. The northern cap is irregular and bright, and curved bands start from it and reach down to the temperate zones of the planet. After the autumnal equinox, which occurs at a time corresponding to the beginning of September on Earth, the white material begins to form in large patches around the pole. These patches join to form a cap which reaches a large dimension and lasts until spring. Just before the equinox, the cap begins to shrink uniformly, so that at the time of the summer solstice it measures only a few hundred miles in diameter and becomes much smaller in the late summer. This region often appears veiled with a yellow tinge, occasionally with a hint of grey, over the whole extension, or in some of its parts. During the period when the cap is shrinking, a dark band appears to divide it into two unequal parts. At the same time a bright patch appears at an areographic longitude of 210°, this is perhaps a higher region where the white material accumulates in a larger quantity. After the disappearance of the polar cap, some faint veils of a bright yellow colour remain, but the pole remains uncovered. The last residual of the white polar cap appears slightly eccentric with reference to the pole. The south pole, unlike the north pole, is situated in the middle of a dark region and consists of bright patches, which are often covered by yellowish veils. Several patches have been carefully observed by

Maggini at the 1924 opposition. These patches break up, and several bright nuclei appear, which are almost like luminous points which have a very short life, lasting only a few minutes. It is not possible to decide whether these are accidental reflections or in fact are real topographical features. At the time of the 1924 opposition, the polar cap at first decreased gradually but then, suddenly, it underwent a strong decrease up to the 79° parallel. The edge of the cap withdrew as far as the dark region 'Depressio Magna', and it is thought that in this region there must exist some special conditions to produce the rapid melting of this white substance. As in the case of the northern polar cap so the southern one is not centred on the rotation pole. When the southern cap is reduced to a minimum, it is eccentric and leaves the pole uncovered. Finally even the small residual disappears at about two months and a half before the autumnal equinox.

The appearance and the phenomena shown by the polar caps would lead us to the conclusion that these regions are periodically covered by snow or ice. If it is not a question of frozen water, it must be at least some substance which melts and evaporates, when the temperature increases in the spring, diffusing in the atmosphere of the planet, only to precipitate again when the surface of the planet becomes cooler. This hypothesis is confirmed by the white patches which can be observed when the Sun rises on the Martian horizon, patches which disappear as soon as the rotation of the planet carries them towards the centre of the disc. Probably here we have a phenomenon of precipitation very similar to that of water vapour on Earth when the temperature is 0° C. or even lower.

If the white substance covering the polar regions of Mars is not frozen water, then it might be frozen carbon dioxide. However, measurements of the temperature of the surface of the planet show that at the poles the temperature during the summer rises above the melting-point of ice, and therefore it is very likely that the polar caps on Mars are indeed covered by snow. The layer cannot, however, be as thick as at our own poles, because the solar heat, which on Mars is only 40% of what the Earth receives, would not be sufficient to melt and evaporate a very large quantity of snow. The maximum depth must be only a few inches.

As in many other astronomical problems, photography has given a valuable contribution to the understanding of the atmosphere of Mars. The planet has been photographed by means of a combination of filters and suitable photographic emulsions sensitive to certain

wavelengths (Plate 23). In this way photographs were obtained in ultraviolet light, in the visible region of the spectrum and in the infrared. The differences which we can see in these photographs are very striking. In the ultraviolet photographs the disc of the planet appears with the largest diameter and, with the exception of the polar caps which seem to be of a greater extension, no other detail is visible. Any spot which may appear on such photographs is only of a transitory character. In the photographs taken in the visible region of the spectrum, the details and features which can be observed visually are present and these become sharper and darker in the infrared photographs. Similar effects can also be detected in photographs of terrestrial landscape taken from the air, with a similar combination of filters and emulsions. We must conclude therefore that there must exist also on Mars an absorbing and diffusing atmosphere. With the infrared photographs we penetrate deeper into the atmosphere of the planet, and probably we see the real aspect of its surface. From the difference of the diameters of the disc in photographs in the short and long wavelengths, it is possible to estimate that the height of the atmosphere must be about 120 miles. Wright, who was among the first to obtain several photographs of this type, has suggested that the polar caps consist of thick clouds suspended in the atmosphere of Mars, which dissolve and evaporate under the effect of the solar radiation. This interpretation may find confirmation in the fact that yellow and white clouds have been detected in the planet. Moreover the white clouds seem to have a preference for higher altitudes, so that these may well be similar to those of a more permanent character around the poles. At the limb of the disc bright prominences have been observed which occasionally are completely detached from the terminator. Antoniadi during the 1924 opposition observed one prominence among others, on 'Hellas'. The highest point of this prominence appeared to vary in four days from 5 to 12 miles above the surface of the planet.

Further useful information on the question of the atmosphere of Mars can be obtained from spectroscopic observations. These investigations are carried out when it is possible to distinguish the absorption lines due to the atmosphere of Mars, or of the Earth, because of the motion of approach, or recession, of the two bodies. Campbell obtained spectrograms of Mars during the 1909 opposition, from Mt. Whitney at 14,500 feet. He reached the conclusion that either the quantity of oxygen and water vapour in the atmosphere of Mars was so small as to be undetectable with the spectroscopic

means at his disposal, or that those substances are too deep in the atmosphere to be detected.

Later, Adams and St. John at Mt. Wilson, with more powerful instruments, carried out similar investigations. They reached the conclusion that at the time of their observations the amount of water vapour present in the atmosphere of Mars was only 6% of that at Mt. Wilson, at a height of nearly 6,500 feet above sea-level, and 3% of that on the plain near the shores of the Pacific. This indicated that over a great part of the Martian hemisphere, visible at the time, and at the beginning of its spring, conditions existed very much like those of a desert.

Similar investigations carried out on the oxygen lines show that in the spectrum of Mars, their intensity is 33% of that of the terrestrial atmosphere. Allowing for the height above sea-level of Mt. Wilson, from where the observations were made, it is found that for a similar area in the atmosphere of Mars there is present only 16% of the oxygen existing above Mt. Wilson. The results of these investigations were of such interest that further observations were made at Mt. Wilson with the 100-inch reflector coupled with a high-dispersion spectrograph mounted at the end of the polar axis. The conclusions reached were that in the atmosphere of Mars all the oxygen and the water vapour, if they do exist, must be in extremely small quantities. In the case of the oxygen, a ratio of even 1 to 1,000 should have produced a detectable asymmetry in the lines of the B band of oxygen observed by Adams and Dunham in the years 1932 and 1933. At that time the radial velocity of the planet relative to the Earth varied from $-8{\cdot}5$ miles/sec. to $+7{\cdot}8$ miles/sec., and the linear scale of the spectrograms was 5·6Å /mm.

The profiles of the oxygen lines were measured by means of a microphotometer and compared with the theoretical profiles, assuming the ratio 1 to 1,000 for the relative abundance of the molecules of free oxygen in the atmosphere of both Mars and the Earth. From the above observations the conclusion is reached that the amount of oxygen in the atmosphere of Mars must be extremely small, certainly less than 1% and very probably less than 0·1% of that existing in the atmosphere of the Earth over equal areas of its surface.

With the same telescope and with a spectrograph having an even higher dispersion, namely 2·9 Å/mm., another investigation was carried out to discover whether water vapour does exist in the atmosphere of Mars. The lines used for these studies were those of the infrared bands and the measurements were made both when Mars

approached the Earth and when it receded, so that the components due to the Martian atmosphere would, if they existed, appear on either side of the lines due to water vapour in the terrestrial atmosphere. The result of the observations indicate that such an effect is almost at the limit of the errors of observation and therefore Adams suggested that if the lines of water vapour are present in the spectrum of the equatorial regions of Mars, they cannot be more intense than 5% of those of the terrestrial atmosphere, and probably much less.

So far, other substances, such as carbon dioxide which at a low temperature may produce the precipitation observed in the polar regions, have not been determined spectroscopically, and in any case, from the observations so far obtained, the conclusion is reached that the atmosphere of Mars must be very rarefied.

The deficiency of oxygen, as revealed by the spectroscope, is not necessarily a decisive proof of its absence on the 'red planet'. This colour must however be due to some gas or substance present on it. Iron oxide could be present, and this would imply that the oxygen was no longer free but was combined chemically with iron. On the Earth we have red rocks which belong to sediments very strongly oxidized, and it may well be that the colour of Mars may have a similar origin.

If the intensifying of the colour of the dark markings of Mars is due to vegetation, evolution processes may be in action so that the plants could then obtain the oxygen they require even if this is no longer free in the atmosphere of the planet. Recent observations made in the United States with the spectroscope pointed first on the bright regions and then on the dark patches of Mars, have shown that the latter reflect violet light. The typical reflection of the terrestrial vegetation is missing, namely that of the chlorophyll, which is very intense in the red.

Lyot has carried out very interesting observations on the polarization of the light reflected by Mars. The surface of the planet is very difficult to study because of the clouds that cover it and which introduce irregularities in the cause of polarization. However, at the time when the planet is clear of clouds, Lyot finds that for a phase angle between 0° and 40°, the curve of polarization is almost identical with that obtained for the Moon. This leads to the suggestion that on the Martian continents there probably exists a fine dust similar to that which covers the surface of the Moon.

The study of the Martian 'maria' presents greater difficulty, but in any case the curve of polarization for these regions seems to be

little different from that for the 'continents'. The southern polar cap has often shown evidence of polarization much stronger than that for terrestrial snow, but its variations could be explained by the frequent formation of clouds over this region. Some of the whitish patches which appear to the east on 'Thyle II' and the 'Aonius Sinus' could consist of transparent particles, like icicles, because when these patches are observed at a very oblique angle, they present a polarization which is very intense as in the case of terrestrial snow. Clouds in similar condition would not show any polarization. The Martian continents, like those of the Moon, do not, in general, show this phenomenon. From these observations it can be deduced that the atmosphere of Mars is very rarefied. Lyot estimates the density of its atmosphere to be $\frac{1}{15}$ of ours.

The temperature observed over the polar caps in the winter of Mars, is about $-70°$ C. We are dealing here with a surface temperature which may well be higher in the lower layers. As the summer solstice is approached, the temperature at the poles rises above freezing. In the equatorial regions the midday temperature rises above freezing up to 10° C. or even more. With such a rarefied atmosphere and with the scarcity of water vapour present, the temperature falls very rapidly when the Sun is low on the horizon of the planet, reaching a minimum night temperature of the order of $-90°$ C. The variation of temperature from day maximum to night minimum, and from season to season, must be very marked. Since it is winter in the northern hemisphere and summer in the southern hemisphere when Mars is nearer to the Sun and vice versa when it is further from the Sun, it follows that the southern hemisphere has a hotter summer season and a colder winter than the northern hemisphere. Both the composition of the atmosphere and the temperature, although very different from those prevailing on Earth, are not such as to make some form of life utterly impossible on Mars.

We have already discussed the seasonal and irregular changes which take place on the surface of the planet. The opinion which is most generally accepted about these changes, is that they are due to the seasonal growth of vegetation which covers the dark regions of the planet, while the other regions are deserts. When the polar caps melt, the water which is evaporated could fall in the form of rain or dew on the regions of lower latitude, thereby favouring the growth of a vegetation which could explain the greenish colour observed in these regions. During the winter the vegetation dies and a grey or

brown colour takes the place of green. The presence of oxygen and carbon dioxide is another argument in favour of the presence of vegetation, even if only in a very primitive form.

Spencer Jones and others have suggested that even if it is probable that on Mars there exists some form of plant life, nevertheless the planet, having lost a great part of its atmosphere and humidity, must be a world where even these elementary forms of life are approaching extinction. On the other hand McLaughlin, a few years ago (1954), put forward a view which is quite opposite to the above. The characteristic configuration of the 'maria', which are funnel-shaped from the southern to the northern hemisphere, has suggested to him the existence on the planet of a system of winds having a well-defined circulation, in some ways similar to that existing on Earth. This may explain the appearance of phenomena very like sand storms. The rather sharp ends of the 'maria' towards the northern hemisphere are, according to McLaughlin, volcanoes whose ash is carried by the winds towards the southern hemisphere. The changes observed in 1926 in 'Solis Lacus' could be explained by some new volcanic eruption, even greater than the terrestrial Krakatoa eruption because very large areas of the disc of the planet were covered by dark clouds for several weeks. It is suggested that the interior of the planet has not yet reached the conditions existing at present on Earth, because of its lower temperature of formation and its smaller force of gravity. The violent volcanic eruptions taking place on Mars would then be the manifestation of the internal disturbances, which will, in due course, bring the planet to a state similar to that of the Earth. Obviously these two views are opposite. One suggests that Mars is a planet on which life is approaching extinction, while the other suggests that the planet, far from being dead, is in fact in the condition in which the Earth was at the time of the first period of the pre-Cambrian era.

It is to be hoped that the continued observations of Mars at the time of favourable oppositions with improved instruments may increase our knowledge of the conditions on Mars.

Until recently most of the observations of Mars had to be made from the Earth and the information obtained was patiently pieced together to give the general picture we have of the planet, a picture which we have described in detail in the previous pages. Now, however, the astronomer can rely on the help of the space probes to obtain observations from a much closer range.

We have already described some of the results of the observations

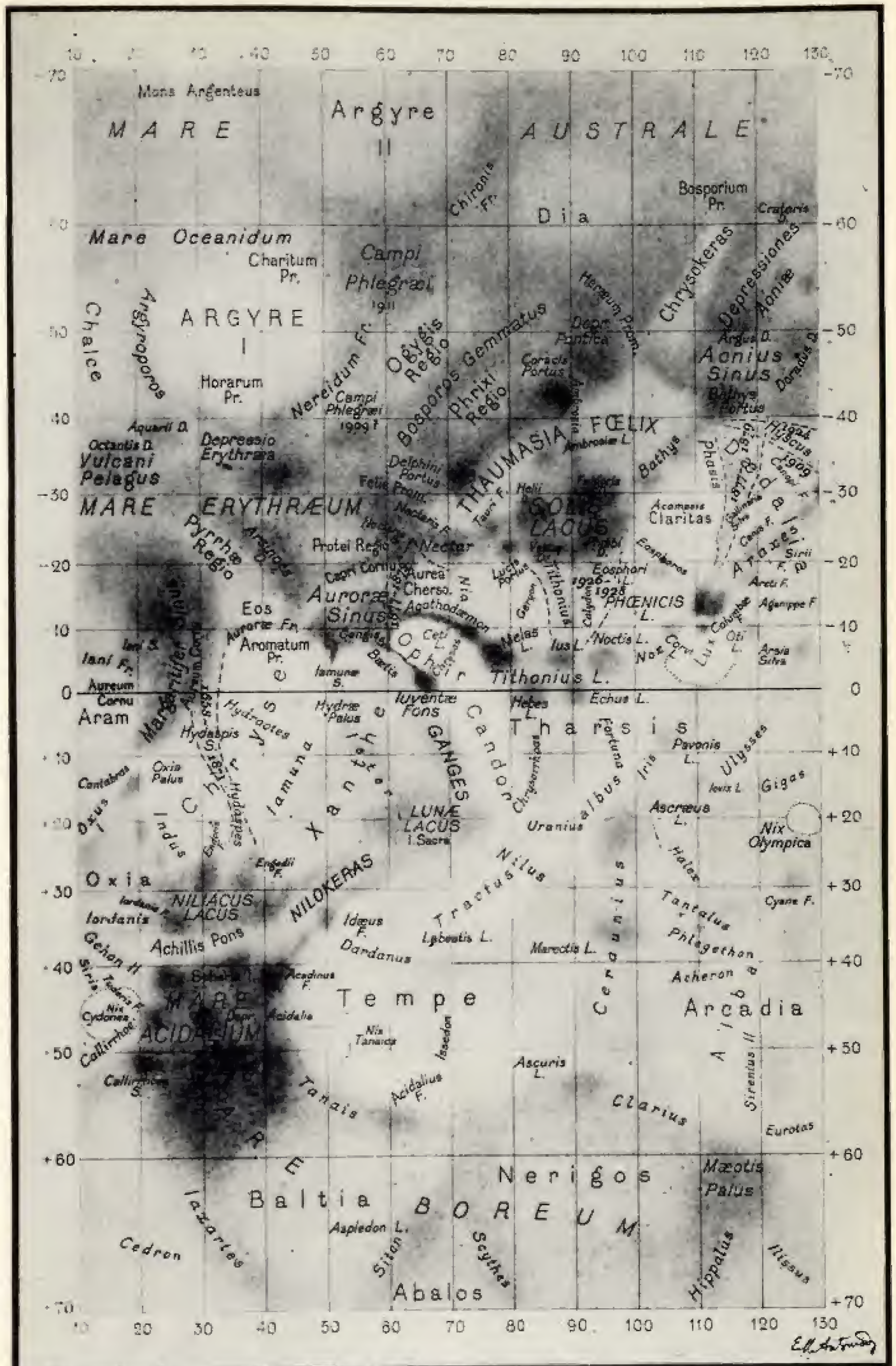


Plate 20. Map of Mars. Drawing by Antoniadi showing the regions Thaumasia Felix, Solis Lacus, Mare Acidalium

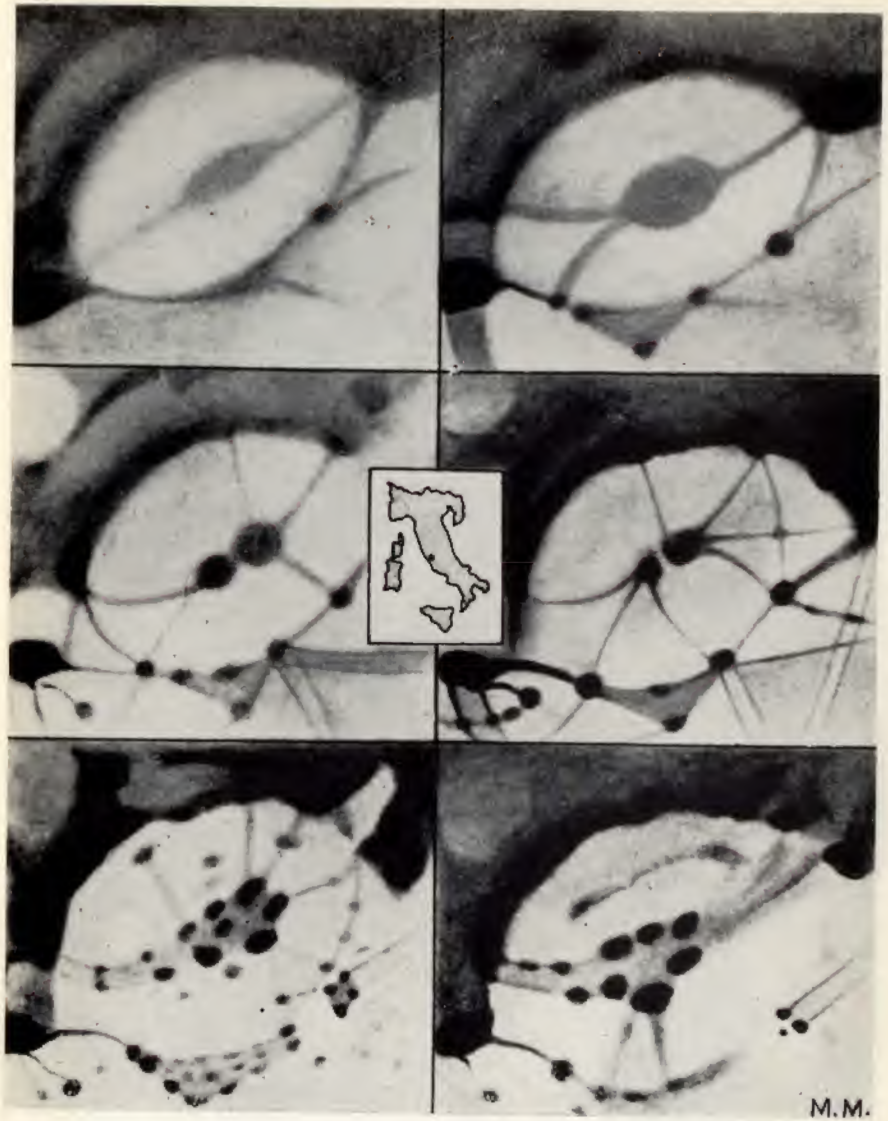


Plate 21. Changes observed in various years in Solis Lacus in the region of Thaumasia Felix, by M. Maggini

(*top*) 1907
(*centre*) 1909–1911
(*bottom*) 1924–1926

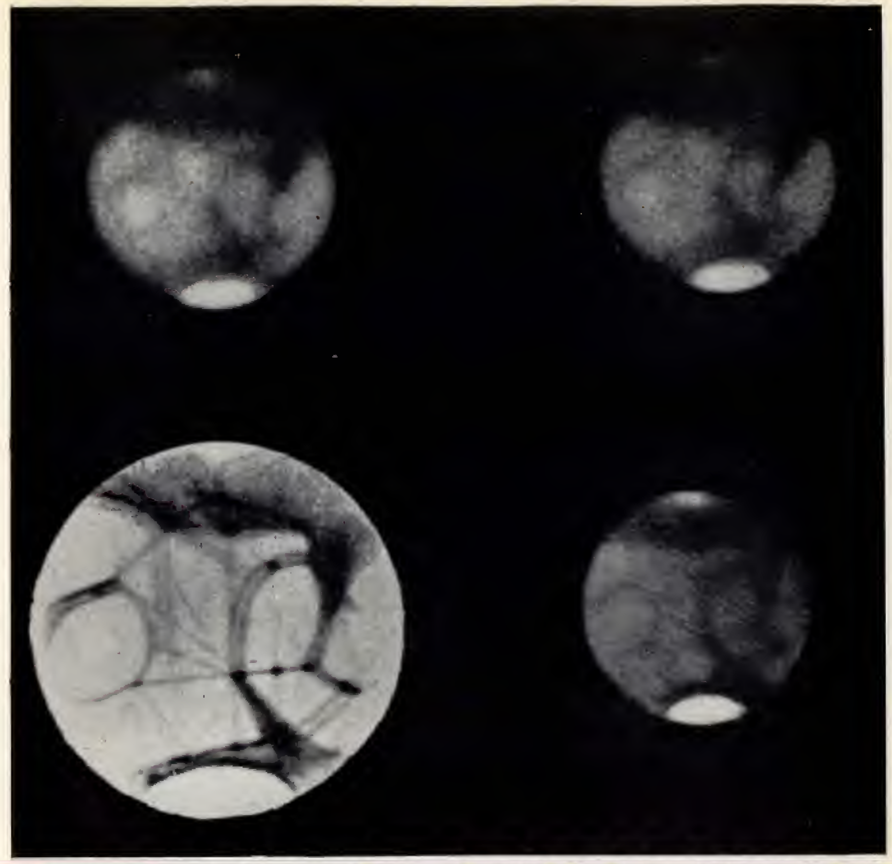


Plate 22. Comparison between photographs of Mars and drawing by E. Slipher. Longitude of the centre of the disc 250°. On this is visible the *Syrtis Major*, lower; the North Pole

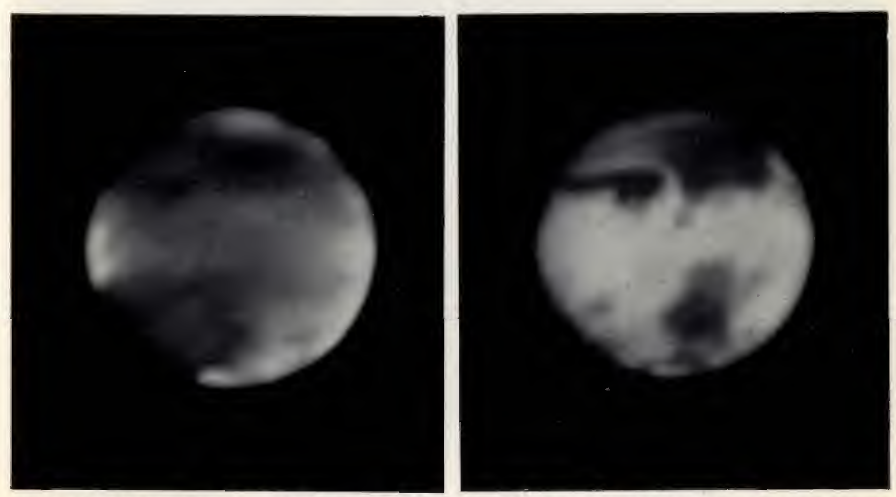


Plate 23. Mars photographed in blue light (*left*) and red light (*right*). 200-inch Hale telescope. Mt. Palomar.

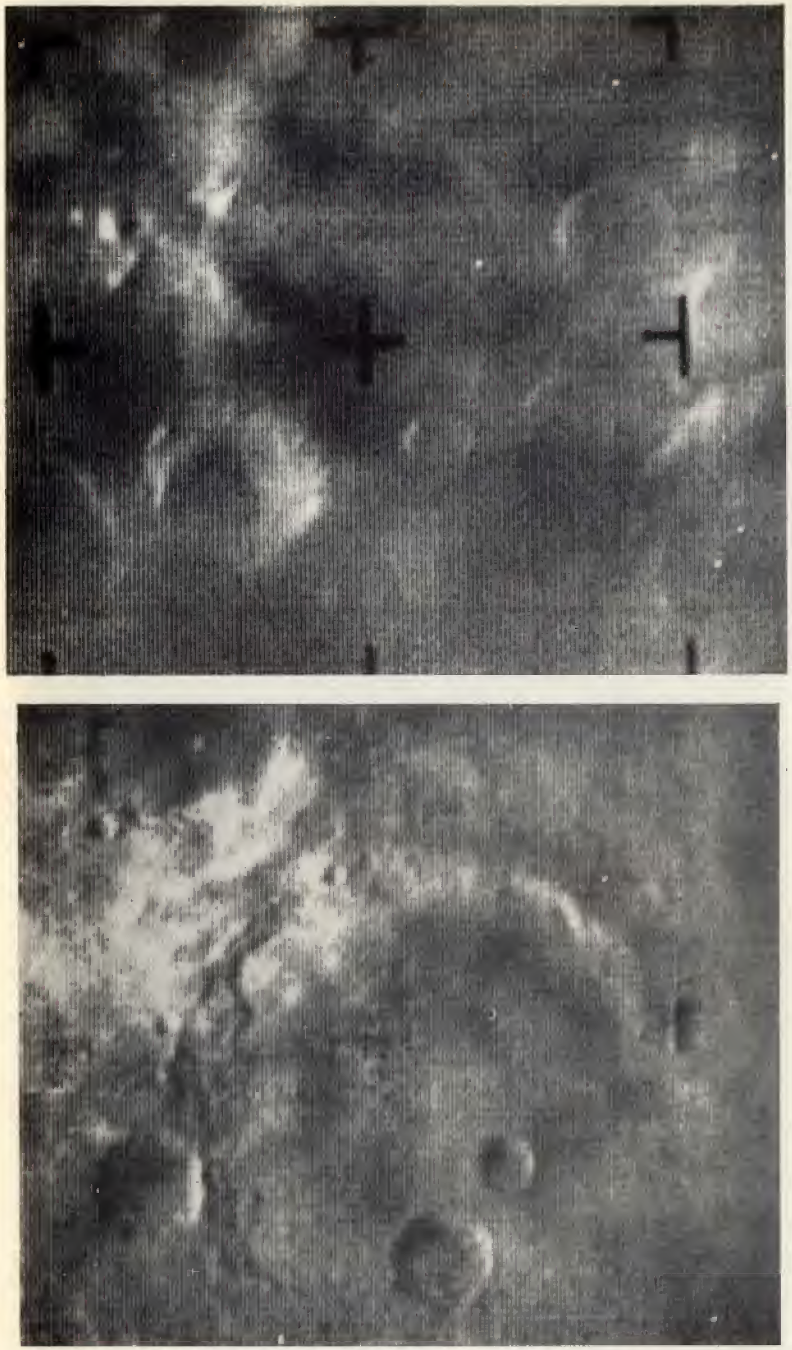


Plate 24. Photographs of Mars taken by Mariner 4, with green filter. *(left)* photograph taken at a distance of 7,800 miles from the surface of Mars, showing Atlantis between Mare Sirenum and Mare Cimmerium. *(right)* photograph taken at a distance of 7,600 miles from the surface of Mars, showing bright region Northwestern Phaetontis. Photographs reproduced by courtesy of U.S.I.S.

and the information collected by Mariner 2 on its mission to Venus. Even more spectacular however has been the recently completed journey of Mariner 4 towards Mars.

Mariner 4 was launched on November 28th 1964 on its long journey towards Mars. It was planned to pass close enough to the planet to send back to Earth photographs of various well-known features of its surface. The mission was completely successful and, as calculated, Mariner 4 reached its closest approach to Mars, 6,118 miles, on July 15th 1965. The transmission of the photographs back to Earth was a complete success in spite of the great distance involved, Mariner 4 being then about 134 million miles from the Earth.

At this stage it is too early to expect any definite results from the study of the 22 photographs, indeed it will be a long time before all the valuable information they contain is analysed and interpreted. However some very startling facts were revealed and perhaps the most unexpected was to find that at least a part of Mars is covered by craters (Plate 24). This may have a very significant meaning in the history and evolution of Mars. Seventy craters ranging from 3 to 75 miles in diameter were counted on some of the photographs received and it is probable that much smaller craters exist. If this is representative of the Martian surface, the total number of craters on the whole planet may well exceed one thousand.

Measurements of the craters in the photographs would suggest that they have rims rising a few hundred feet above the nearby surface. Some of the craters which are at latitudes where the Martian winter was in progress, appear to be rimmed with frost.

From the photographs available of the Martian surface it appears that no formations similar to terrestrial ones, such as mountain ranges, valleys and oceans, can be detected. The question of the 'canals' still remains unanswered in spite of the fact that Mariner 4 passed over some of the 'canals' which appear on maps sketched from terrestrial observations.

At this very early stage it is not yet possible to reach any definite conclusions about the Mariner 4 mission. However the American scientists have drawn some general inferences from the photographs. These can be summarized thus:

1. From the evidence of the craters on the surface of the planet it is probable that its age is between two and five thousand million years.

2. The fact that this surface appears to be well preserved may

suggest that its atmosphere was never much denser than it is at present. It is unlikely that water had ever existed in large quantities on the surface of Mars as its presence would then have been responsible for severe erosion over the whole surface of the planet, and this is not evident.

3. Mars does not appear to have a magnetic field.

4. As it was expected the photographs neither prove nor preclude the possible existence of life on Mars.

There are still many unanswered questions concerning Mars and indeed the results of the observations of Mariner 4 have in many respects opened new fields of investigations. At present another similar expedition is not being considered but the American scientists are going ahead with preparations for the 'Voyager' project, which is intended to soft-land on Mars a capsule containing various instruments.

Astronomers await with great interest the results of this project which if successful will lead to a better understanding of the constitution, history and evolution of the 'red planet'.

Two satellites revolve around Mars, namely Phobos and Deimos. Both are very small, the diameter of them being of the order of a few miles. They are visible from Earth when Mars is at opposition, by using telescopes which can reach 12 and 13 magnitudes.

The mean distance of Phobos and Deimos from Mars is 5,800 miles and 14,600 miles respectively. The period of revolution of the first is 7 hours 39 minutes and of the second 30 hours and 18 minutes. Phobos is the only satellite of the solar system which has a period of revolution shorter than the period of rotation of its planet. The result of this is that, seen from Mars, Phobos rises in the west and sets in the east, performing its peculiar diurnal retrograde revolution in about 11 hours, while Deimos rises in the east and takes nearly 132 hours to complete its revolution. The orbits of the two satellites are almost circular. That of Phobos has an inclination to the equator of Mars of 0° 57′, and that of Deimos 1° 44′. Since these satellites are so small and so near to the planet, they are very difficult to observe.

CHAPTER VII

The Asteroids

The asteroids are very small bodies of very low brightness, which describe elliptical orbits around the Sun and which are almost all between the orbits of Mars and Jupiter.

The first asteroid was discovered by Piazzi at Palermo on January 1, 1801. He gave to it the name of 'Ceres', the goddess of Sicily. These small bodies were at first known as 'little planets', but W. Herschel introduced the name asteroids, because their appearance was much more like that of a star than a planet.

If we consider all these bodies as forming one single family, then, according to Titius' law (see p. 233), it would occupy the position of a missing planet between Mars and Jupiter, which ought to be at a distance of 2·8 A.U. from the Sun. The average distance of the brightest asteroids is in good agreement with this value.

After Piazzi's discovery, many followed both by means of visual and photographic observations. The introduction of photography for this type of work has made possible the discovery of asteroids down to the very faint magnitudes reached by the telescopes, and their number has increased considerably. The number of asteroids discovered, for which the orbit could be calculated, is 1,500. However, according to an investigation carried out by Baade with the 100-inch reflector at Mt. Wilson, in the neighbourhood of the ecliptic where asteroids are more frequent, it would appear that if we take as a limit the 19th magnitude there must be about 45,000 asteroids. The work involved in the discovery, observation, calculation of orbits and ephemerides has become very great indeed, and cannot be carried out by a single observatory. Several observatories co-operate in this particular field, among which are that of Heidelberg, the American Centre for asteroids at Cincinnati and the Leningrad Observatory.

These observatories collect and co-ordinate the observations, carry out the necessary computations and publish yearly up-to-date lists of the asteroids, their orbits and their ephemerides.

Almost all the asteroids have a name which was given to them either by the discoverer or by the computer of the orbit. Many of the asteroids have names which have a mythological origin, or they are named after countries, towns and even people. So besides Ceres, Pallas, Juno and Vesta, which are the first four of the asteroids discovered, we have Penelope, Xanthippe, and there are others which reveal the nationality of whoever suggested them, namely Bononia, Padua, Brixia. Names of famous men in many fields of human activities are also found, such as Piazzia, Galilea, Gaussia, Schwarzschilda, Nansenia and Hooveria.

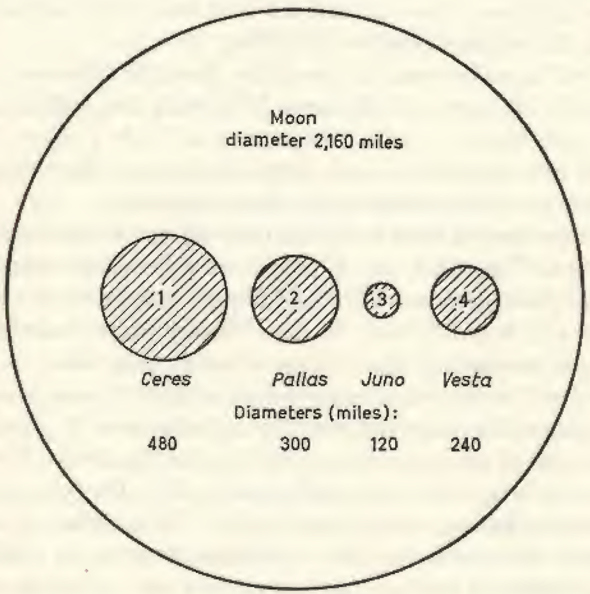


FIG. 38. Dimensions of the first four asteroids discovered compared with that of the Moon.

The dimensions of the asteroids, compared with those of the planets, are very small (fig. 38). From Ceres and Pallas, having a diameter of less than 500 miles, we gradually descend to very small ones having a diameter of barely half a mile and which, therefore, are in reality only pieces of rock comparable to meteorites.

The origin of this ring of asteroids, which are between Mars and Jupiter, with the exception of a few, must be linked to the origin of the solar system. The hypothesis that the asteroids were produced from the explosion of a planet, exploded by internal forces, seems to be the most plausible. The planet, however, must have been a very small one, since the total mass of all asteroids amounts to only $\frac{1}{10}$ of that of the Moon.

Another hypothesis suggested is that the ring of asteroids is the final product of the disintegration of a comet captured by Jupiter, since there appear to be many similarities between asteroids and comets. The origin of the comets, however, is even more mysterious and therefore, at present at least, no final conclusion can be reached.

After the discovery of the brighter asteroids, it became possible, with the more powerful telescopes which became available, to observe a greater number of fainter asteroids. At present the greatest number of asteroids is between 14th and 15th magnitude. Only 20% of the newly discovered asteroids have been observed sufficiently to enable the accurate calculation of their orbits. The majority appear to have an eccentricity between 0·1 and 0·2. Among the known asteroids, those which are nearest to the Sun are Eros and Hungaria. Their respective mean distances are 1·5 and 1·9 A.U. and their respective periods 1·76 and 2·71 years. The furthest from the Sun is Hidalgo at a mean distance of 5·71 A.U. and having a period of 13·7 years. This asteroid has an orbit with a high eccentricity (0·66). As a result its distance from the Sun varies from 2 A.U. at perihelion to 9·6 A.U. at aphelion, that is from a little beyond the orbit of Mars to almost the distance of Saturn (fig. 39), and its brightness varies from magnitude 10 to magnitude 19.

The periods of revolution of the asteroids around the Sun are distributed in a very irregular and interesting way. Generally they are between 3·25 years to 6 years, although some gaps seem to exist. The average inclination of their orbits is of 10°, several asteroids having, however, a much higher inclination. The direction of motion of all asteroids around the Sun is the same as that of the planets. As a consequence of the fact that the inclination of the orbits of the asteroids is rather small, the majority of them are discovered nearer the ecliptic. When an asteroid is discovered further away, this means that either the inclination of its orbit is greater, or that the asteroid is very near to the Earth.

Comparing periods, eccentricity and inclination of the orbits, we

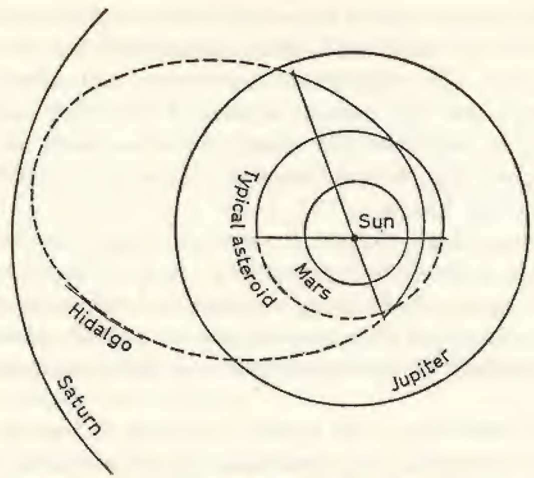


Fig. 39. Orbits of a typical asteroid and of Hidalgo.

find that there exists some sort of relationship between these quantities. With a few exceptions, the eccentricities of the orbits are all small, irrespective of the length of the periods. There is a great scarcity of great inclinations for periods shorter than 3·5 years. For periods included between 7 and 10 years, the inclinations of the orbits are all small, while for longer periods, of the order of 12 years, the inclinations are very variable. The shape and orientation of the orbits of the asteroids depend, at least in part, upon their period. The density of the asteroids is not very different from that of the terrestrial crust, in other words they are of the same density as that of the Moon. The masses are very small indeed, that of Ceres, for instance, is $\frac{1}{8,000}$ of that of the Earth. It can therefore be assumed that all asteroids lack an atmosphere.

As a result of the gravitational force, which is predominant in such small bodies, it may well be that the asteroids are not spherical in shape. A proof of this can be found in the fluctuations of the brightness in some of them. For example Iris and Eros are variable with a period of 6 hours and 5 hours 16 minutes respectively. It is natural to think that these values are also those of the period of rotation of the two asteroids. From the light-curves and the distribution of their maxima it is possible to deduce whether the variation in brightness is due to a difference in the albedo of the opposite sides of the asteroids, or to the irregularity of their shape.

When discussing the distribution of the periods of the asteroids,

we said that they seem to be included between 3 and 6 years, but that some gaps exist. The most conspicuous gaps occur for the periods of 5·9, 4·8 and 4·0 years, namely exactly one-half, two-fifths and one-third of the period of Jupiter, which with its large mass exerts a great influence upon the distribution of the orbits of the asteroids. The motion of those asteroids which are in resonance with Jupiter, because of its attraction in the same points of the orbit, is subject to rhythmical variations, which have the effect of forcing the asteroid into specific orbits.

Brown has studied the orbits having a period of 6 years and he found that neither their size nor their shape could remain constant. Moreover he found that periods which are within 25 days from the critical value must change rapidly. At any particular time very few asteroids could have periods within these limits. The position and magnitude of this gap have been confirmed by observations. Although the theory is still rather incomplete, there is no doubt that the distribution of the various gaps, known as Kirkwood's gaps, is due to the cumulative effects of perturbation produced by Jupiter.

Since 1906 some asteroids have been discovered which form the group called the 'Trojan Group' from the names they bear; namely Achilles, Patroclus, Hector, Priamus, etc. These objects have distances and periods which are approximately the same as those of Jupiter. From the point of view of celestial mechanics this group of asteroids is extremely interesting since it presents a good example of the 'problem of three bodies' already foreseen by Lagrange. The Sun, Jupiter and each Trojan asteroid always form an equilateral triangle, and the Trojan asteroid will remain in the same position with relation to the Sun and Jupiter, when certain dynamical conditions are satisfied. So far twelve asteroids have been discovered which belong to the Trojan Group, and their orbits have small eccentricity and great inclination. On account of the gravitational attraction of the other large planets like Saturn, the Trojan asteroids occasionally wander from their position at the corner of the equilateral triangle. In this case, if the asteroids come too near to Jupiter, their orbits may undergo a radical change and lose the characteristics of the group. On the other hand an asteroid can be captured by Jupiter and become one of the Trojan Group. It is quite possible that many of them originated in the region between Jupiter and Saturn, and that they cannot be seen because of their considerable distance from us.

The majority of the absolute magnitudes of the asteroids already discovered is included between magnitude 7 and 12. Their number increases rapidly with the decrease of brightness, approximately at the rate of 2·7 times for each magnitude, so that the fainter asteroids, which are yet to be discovered, must be very numerous.

Several asteroids have been discovered which can come very close to the Earth. One of them is Eros, which was discovered in 1898 and which may come as close as 14 million miles from us. In doing so it crosses the orbit of Mars and gives us the opportunity of making accurate determinations of the fundamental astronomical unit of distance. In fact at such a small distance, we can obtain very accurate values for its parallax, and once the orbit of the asteroid is calculated, the parallax of the Sun, namely its distance from the Earth, can be obtained with an error which is much smaller than by any other direct methods.

In 1931 Eros came very close to the Earth. An international programme was evolved and many observatories, distributed all over the Earth, took a large number of observations, in order to determine the parallax of the Sun. The asteroid, on account of its approach to the Earth, is subject to strong perturbations, and from these it was possible to obtain a very reliable value for the ratio of the mass of the Earth to that of the Sun and hence the solar parallax could be obtained very accurately.

The diameter of Eros is not much more than 15 miles. At perihelion it can almost be seen by the unaided eye, having an apparent magnitude of 7·2, comparable with that of the first four asteroids discovered. Eros shows periodic variations of brightness, probably due to its rotation, which has a period of 5 hours 16 minutes, and it has two maxima and two minima of brightness.

In 1936 a small asteroid was discovered at Uccle Observatory. The orbit of this asteroid crosses that of Venus and of the Earth and it comes as near as 1·5 million miles to us, that is only approximately 6 times the distance of the Moon from the Earth. This asteroid, of the same class as Eros, was called Adonis by its discoverer Delporte.

There are two more asteroids belonging to the same family, namely, Apollo, discovered in 1932 and which can come even closer to the Earth, and Icarus (see p. 317) which was discovered in 1949.

In 1937 Reinmuth, at the Heidelberg Observatory, discovered an object of the 9th magnitude endowed with a very great speed, which

came even closer to the Earth. Had it not been for the trail on a photographic plate, which showed that this was an asteroid, it might well have been thought that here was a comet on account of the speed of its motion. Once the announcement of the discovery was made, many observers were able to make a number of observations, but only for a few days, since in less than four days this asteroid had crossed the sky from one side to the other. On October 31 its motion among the stars was at the rate of 5° an hour. This means that its displacement in the sky was ten times faster than that of the Moon.

Calculations from the few observations which it was possible to make in the short time, showed that the asteroid had an orbit which had a very small inclination to the ecliptic and that it crossed the ecliptic at a point very near to that where the Earth was at the time of the discovery. This very interesting object was called Hermes and it came extremely close to the Earth on October 30, when its distance was only 435,000 miles. From its brightness it appeared that the diameter of Hermes must have been a little more than half a mile. On account of the speed of travel of Hermes and of its distance from the Earth, there was no question of it being attracted and falling on the Earth. In this case we are at the limit between asteroids and meteorites of comparable size which, as we shall see later, have fallen on the Earth.

Unfortunately Adonis, Apollo and Hermes could be observed only for a very short time and therefore their orbits are not accurately known. There is little hope that they may be observed again when next they pass near the Earth. The chance of discovering them again is rather remote, because of the orientation that their orbits must have in order to cross the ecliptic when they approach the Sun. This leads to the thought that there must exist a much greater number of asteroids of this type than we know of at present.

It seems that there may exist more groupings of asteroids like the above or like the Trojans forming families of asteroids. This would strengthen the hypothesis explaining their origin, that they were formed by the explosion of one or more bodies which had appeared as a result of the original cataclysm.

Jupiter with its perturbations would then have been responsible for the gradual displacement of their orbits which originally were very similar to each other. As time went by, the perturbations were unable, however, to change the average distances of the asteroids and the inclination of their orbits with respect to the orbit of Jupiter, but created certain conditions which, according to the investigations

of Hirayama, appear to be satisfied in the case of some of the families of asteroids. At present, however, we cannot state to what extent the hypothetical explosion was responsible for the general distribution of the asteroids.

CHAPTER VIII

Jupiter and Its Satellites

Jupiter is the largest of the planets of the solar system. Its mean distance from the Sun is 483 million miles. It revolves around the Sun with a sidereal period of 11·86 years and with an orbital velocity of about 8 miles/sec. The orbit has an eccentricity of 0·048 and its inclination to the ecliptic is 1° 18′. The mean diameter of Jupiter is 85,750 miles, that is nearly 11 times that of the Earth, while its mass and volume are respectively 318 and 1,312 times those of the Earth. The mean density of the planet is 1·34 that of water. The apparent angular diameter varies between 50″ when at a favourable opposition, to 31″ when at conjunction, while its apparent magnitude when at the most favourable opposition is −2·2. The oblateness of Jupiter is very perceptible, being, according to Struve, 1/15·4 and its albedo is 0·44, which is a rather high value. As in the case of the Sun and of Saturn the centre of the disc appears much brighter than the limb. This phenomenon, which is not apparent either in Mars or the Moon, indicates the existence of an atmosphere which absorbs some of the light of the reflecting surface of the planet (Plate 25).

The disc of Jupiter appears crossed by coloured bands which are parallel to its equator. This appearance is probably due to atmospheric phenomena, possibly clouds, of a yellowish-white colour, called 'zones', which alternate with dark 'belts' of a brown colour. These markings are very clearly visible and enable an observer to determine with good accuracy the period of rotation of the planet around its axis. The early measurements were made by Cassini. The mean value of the rotation period is about 9 hours 52 minutes, but it appeared, however, that various features of the planet gave different values for the period of rotation, either because of their own motion or for other reasons. Each zone and belt has its own period of rotation, and the spots which are found in them can also have

strong motions of their own. The rotation period is shortest at the equator, being 9 hours 50 minutes 26 seconds, but there is no evidence here of a gradual variation with latitude as in the case of the Sun. Jupiter therefore does not rotate like a solid body, but with various velocities according to the markings observed and their latitudes. There exist several 'surface currents' which move with different well-defined velocities. The great equatorial current covers a zone nearly 12,000 miles wide. At higher latitudes, in both hemispheres, there are the tropical, temperate and polar currents which have periods ranging from 9 hours 55 minutes 5 seconds to 9 hours 55 minutes 54 seconds, without any particular order. Some of these have a motion of their own which can reach a velocity of 186 miles/hour.

The most striking feature of the surface of Jupiter is the 'Red Spot', which is found at 26° of latitude south and seems to have changed very little since the days of the early observations of the surface of the planet. The shape of this red spot is elliptical, 30,000 miles long and 7,000 miles wide. The brick-red colour, characteristic of the spot, may become very faint, when the spot decreases in intensity. When the spot becomes almost invisible, its place is marked by a sort of crater above the large southern belt. In the belt, south of the spot, there is a dark region probably related to it, which has been called the 'south tropical disturbance'. Observations made during the last sixty years or so have given 9 hours 55 minutes 40 seconds for the period of rotation of the red spot. During the same period, the red spot has drifted between positions which are as much as 20,000 miles on either side of its mean position and has also moved through several thousand miles in latitude. The period of rotation of the 'south tropical disturbance' is 9 hours 55 minutes 20 seconds. This means that it overtakes the red spot about every two years, forming around it a circulation of vapours with a velocity of 16 miles/hour. When this happens the motion of the 'tropical disturbance' appears to accelerate, and the red spot seems to be dragged for several thousand miles in the direction of the current which surrounds it, after which the spot appears to be left behind. From all this it is clear that both these features move in a fluid medium and are not attached to anything solid on the surface of the planet.

It is probable that on Jupiter eruptions of gaseous matter or vapours occur. These would rise towards the external layers and take a more stable appearance. The rotation of Jupiter is much faster

than that of the Earth. Its equatorial region rotates with a velocity of nearly 466 miles per minute as compared with 17 miles per minute in the case of the Earth. The very high velocity not only produces the considerable flattening at the poles and bulging at the equator, but is also responsible for the variations of some of the mobile features, which are probably elastic, on the surface of the planet, and which group themselves into zones or belts parallel to the equator. These variations sometimes take place on a gigantic scale. For instance in the last sixty years, both the south tropical disturbance and the red spot have shown great irregularities in their motion.

For the study of the motions which take place on the surface of Jupiter, it is usual to consider two periods of rotation, the first of 9 hours 50 minutes 30 seconds and the second of 9 hours 55 minutes 41 seconds, so that the motion of the various markings can be easily compared with these periods. The first of these represents the motion of the equatorial markings, while the second refers to all the markings outside this zone and hence includes the red spot.

Taffara, who made many observations of Jupiter during the 1928 and 1929 oppositions, called attention to the fact that the periods of rotation of the more stable features, which are distributed at various latitudes, do not differ very much from each other. Their differences are well within the limit of the mean error, so that the longer of the two periods given above can be taken to represent the probable period of rotation of Jupiter. The greater velocity which is observed in the equatorial zone can be attributed to the vapours which are to be found there and which rotate with the zone with rapid variations. If we are dealing here with layers of clouds, which are rapidly blown by an equatorial current, we may consider this current to be in a way similar to those existing in our upper atmosphere and in the solar atmosphere. The structure of Jupiter's belts, which are often crossed diagonally by lighter stripes, is reminiscent of the trade wind belts on the Earth, particularly in view of the fact that some of the characteristics of the equatorial clouds of the planet call to mind the terrestrial clouds.

Father Secchi called attention to the similarity between the meteorology of the two planets, which could in part be due to the cycle of solar activity. The physical conditions of Jupiter are, however, very different from those of our Earth and any analogy existing can be only very vague. It could well be that on Jupiter we witness real eruptions from its interior and that we observe only the highest

parts of them, as in the case of the Sun. Taffara remarks that the spots on Jupiter when they become dense, form a long trail, very similar to smoke, which in expanding envelops the planet in long belts. This phenomenon could be compared with the pine-tree shaped clouds produced by terrestrial eruptions, which at first rise with such a density as to appear almost solid, and then, when they explode, become very widespread and are dispersed by the upper air currents.

Spectroscopic analysis of Jupiter shows that the spectrum is due to reflected sunlight. In the red there are found intense bands which are due to absorption by the atmosphere of the planet. These bands, which with high dispersion can be separated into fine lines, are also present in the spectra of Saturn, Uranus and Neptune. Until a few years ago it was not known which molecules were responsible for these bands. Wildt showed that the band which covers the region of the spectrum from λ 6450 Å to λ 6507 Å is the same as that found in the absorption spectrum of ammonia gas (NH_3). Slipher was able also to photograph other bands in the region of λ 7200 Å and at other wavelengths between λ 8000 Å and λ 8600 Å, which can be attributed some to ammonia and others to methane (CH_4).

Later, Dunham at Mt. Wilson, by using a high-dispersion spectrograph was able to resolve the bands into a large number of lines which could be compared with laboratory spectra. The method adopted was the following. A beam of light was made to pass twice through a tube 66 feet long filled with ammonia at atmospheric pressure. The spectrum of absorption of a column 132 feet long of ammonia was then obtained by means of a spectrograph which had the same grating as the one used for the study of the spectrum of Jupiter. The comparison of the two spectra showed a close similarity between the structure of the bands in the spectrum of the planet and those obtained in the laboratory. From the intensity of the bands in both spectra it appeared that the amount of ammonia, over the unit area of the reflecting surface of Jupiter, corresponds approximately to a depth of 16 to 33 feet of this gas in the same conditions as those of the laboratory experiment. The relative intensity of the individual lines in the spectrum of Jupiter is often different from that of the spectrum obtained in the laboratory. It is likely that these differences are produced by differences in temperature. If that is so, from the study of these differences we shall be able to determine the temperature of the absorbing layers of the planet.

The band between λ 8380 Å and λ 8420 Å, in the spectrum of

Jupiter, shows two maxima and can be resolved into a great number of lines. The identification of methane has been confirmed by the agreement of the relative position of 18 lines in the band λ 8640 Å which are present both in the spectrum of the planet and in the absorption spectrum of methane. In addition there is found, in the spectrum of Jupiter, an intense absorption band in the region of λ 9750 Å and four more bands, less intense but very broad, between λ 9750 Å and λ 10,000 Å.

Bobrovnikoff has also observed some differences between the spectra of various parts of the disc of Jupiter, in particular between those of the equatorial belts and those of the polar regions. Ammonia does not appear to play an important part in the formation of the equatorial belts, and these probably are located at a very low level in the atmosphere of the planet. The situation is analogous to the formation of terrestrial clouds, which have no influence upon the inert gases which exist in the higher layers of the atmosphere.

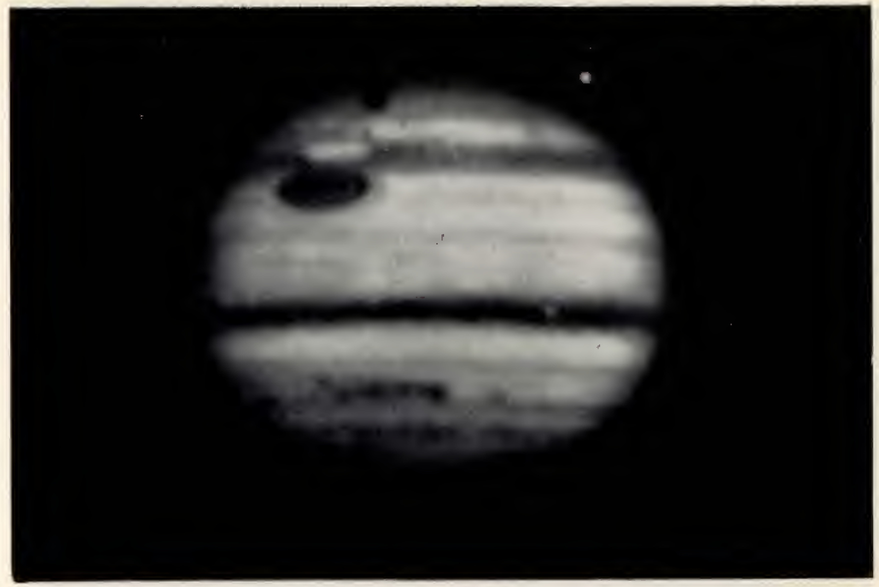
Russell has pointed out that a layer of ammonia 16 to 33 feet thick would produce, by its weight, in the gravitational field of Jupiter, a pressure equal to $\frac{1}{500}$ of our atmosphere. The vapour pressure of ammonia reaches this value when the temperature is —107° C., so that if the atmosphere of the planet had an even lower temperature, it would not be able to contain as much ammonia as has been observed. On the other hand, in an atmosphere which is mainly composed of hydrogen, the pressure of ammonia would be much lower, so that the limit of temperature can be estimated to be —120° C. The clouds which are observed on the surface of Jupiter could then consist mainly of droplets of condensed ammonia. A rotating black body heated by the Sun and at the distance of Jupiter would have a mean surface temperature of —150° C., but the ammonia bands in the spectrum show that the temperature existing on the planet is much higher. This discrepancy could be explained either by the existence of a residual heat in the interior of the planet, or, as in the case of the Earth, by a strong absorption of long wavelengths in the atmosphere, which prevents the solar heat received by the clouds from being easily radiated back.

From what we have said about the origin of the planets from the Sun, the large planets, namely Jupiter, Saturn, Uranus and Neptune, must have kept most of the original amount of hydrogen. In the progressive cooling the nucleus of molten metals must have been still surrounded by hydrogen, helium, oxygen, nitrogen and small quantities of inert gases. The atmosphere has continued to cool and the

nitrogen has then combined with the hydrogen to produce ammonia. The final result at the present temperature of the large planets is that their atmosphere must consist predominantly of hydrogen and small proportions of helium, argon and neon. Water vapour could not exist, because of the temperature, neither could carbon dioxide nor nitrogen, but only methane and ammonia, and these, in fact, are observed.

The nature of the belts, of the red spot and of the south tropical disturbance on Jupiter is still a mystery. It could well be that the colouring observed is due to small quantities of metals, such as sodium, for example, which have become iridescent. With reference to the red spot Wildt has put forward the hypothesis that it might be a large solid mass of hydrogen which floats like an enormous iceberg, in the gases of which the atmosphere is composed. The gases would have to circulate around the spot without actually crossing it, and this is in fact observed. It is true to say that the phenomena of the red spot, of the circulation and of the changes of colour are not yet understood, but are being very closely observed and studied by astronomers when the planet is at opposition.

In spite of the fact that Jupiter presents only small phase angles because of its distance from the Sun, Lyot was able to make some observations of the polarized light reflected by the various parts of the surface of the planet. He found that, near the centre of the disc, the polarization is very uniform and varies regularly with the direction of the incident rays. Near the poles, on the other hand, the polarization which is observed at the limb, near the equator, shows the presence of a dense atmosphere above the clouds, which has a very high diffusion power, similar to that of our own atmosphere in clear weather. The light which reaches us from the limb of the planet is strongly polarized in a plane parallel to it, possibly as a result of a mechanism similar to that which produces the neutral points and the horizontal polarization observed on the Earth in a direction opposite to the Sun. The polar caps show peculiar polarization, which could be explained by the existence, below the clouds, of a dense atmosphere or a strongly diffusing atmosphere which would produce the bluish light observed. The atmosphere becomes more veiled as we move towards the equator, and this would be responsible for the decrease we observe in polarization. Similar investigations have also been carried out by Maggini. He concludes that the gas particles forming the dark spots of Jupiter, are in actual fact smaller than those in the lighter spots. The latter represent a more



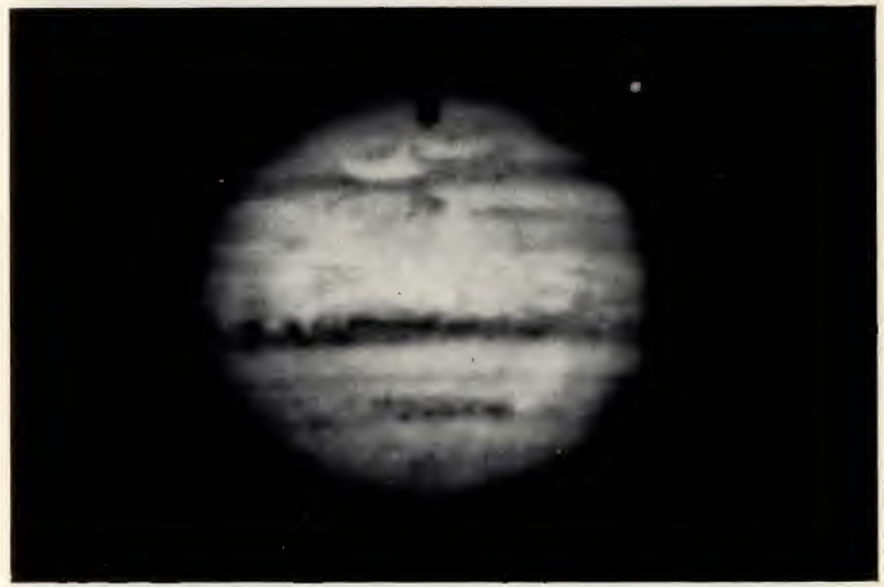


Plate 25. Jupiter photographed (*above*) in blue light and (*below*) in red light. Showing Great Red Spot and satellite Ganymede and shadow. 200-inch Mt. Palomar

Plate 26. Saturn, photographed in blue light. 200-inch Mt. Palomar

Plate 27. Saturn's ring seen edgeways. Drawn by M. Maggini on 23 June 1936 at Collurania Observatory

advanced stage of condensation of the gases, a stage which could go as far as becoming clouds of solid particles.

From all the visual, photographic and spectroscopic observations which can be carried out on Jupiter and the other major planets, it is clear that they are very different from the smaller, solid planets. The atmosphere of the large planets lacks oxygen and water vapour and contains instead large quantities of poisonous gases. Cold, frozen worlds in which life, as we understand it on Earth, could not exist.

In recent years astronomers have discovered new satellites of Jupiter so that now the number has increased to twelve. The first four were discovered by Galileo in 1610 and he called them the 'Medicean Stars'. Later, however, these satellites were named Io, Europa, Ganymede and Callisto, the order being that of their distance from Jupiter. These names, however, are not usually used and the more common usage is that of numbering them with Roman numerals I, II, III, IV. Their apparent magnitude is between 5 and 6, therefore if it were not for the fact that they are so near to the bright disc of Jupiter, they would be seen without the aid of a telescope.

The fifth satellite, which is rather faint, was discovered by Barnard in 1892, with the help of a much more powerful telescope than the one available to Galileo. This satellite has the distinction of being the last satellite of the solar system to be discovered visually. After this, all the later discoveries of satellites were made by photographic means. In 1904 and 1905 Perrine discovered two more satellites, Melotte at Greenwich in 1908 discovered the eighth, and the ninth was discovered by Nicholson at Mt. Wilson in 1914. Later, in 1938, Nicholson, while photographing the ninth satellite, detected on his plates very faint traces due to two other bodies which were interpreted as being two more satellites of Jupiter and were estimated as being of nearly 19th magnitude and therefore were almost at the limit of the instrument used. In 1951, Nicholson discovered yet another satellite of Jupiter, the twelfth. This last satellite is also of 19th magnitude and has characteristics which are very similar to those of satellites VIII, IX, and XI.

The periods of the four major satellites are approximately 1 day 18 hours 28 minutes, 3 days 13 hours 14 minutes, 7 days 3 hours 43 minutes, and 16 days 16 hours 32 minutes; and their distance from Jupiter is 262,000 miles, 417,000 miles, 664,000 miles, and 1,169,000 miles respectively. The orbits are almost circular and are very near to the equatorial plane of Jupiter, the greatest inclination

being only 28′ in the case of satellite II and the greatest eccentricity being 0·0075 for IV. The magnitude of these four major satellites when at mean opposition is 5·5, 5·7, 5·1, and 6·3 respectively; and their diameters are 2,470 miles, 2,060 miles, 3,580 miles, and 3,360 miles. From these values we see that I and II are almost of the same size as our own Moon, while the other two are a little larger than Mercury. Since the specific gravity of the four satellites is 2·9, 2·9, 2·2 and 0·6 it is probable that I and II, like our Moon, have a rocky composition.

When the satellites happen to pass between the Sun and Jupiter, their dark shadows can distinctly be seen projected on the disc of the planet, while when they happen to pass between the Earth and Jupiter, and therefore cross its disc, they are barely visible. This shows that the albedo of the satellites is not very different from that of Jupiter. However, it is noticeable that II is brighter than the brightest parts of the planet and that IV is the darkest of all the four satellites, indeed it is almost as dark as its shadow.

Satellite V is the nearest to Jupiter, its distance being 113,000 miles. Its period of revolution is 11 hours 57 minutes 23 seconds, which means that it is visible each night only for a few hours. Its magnitude at mean opposition is 13 and its diameter is only about 150 miles.

In figure 40 we have given the orbits of the first eleven satellites, from which we can see the very large gap existing between the first five satellites and the sixth, and perhaps this is somehow related to the origin of the satellites. Satellite VI has a mean distance from Jupiter of 7,114,000 miles and a period of 251 days, while satellite IX, which is the furthest, is at a distance of 15 million miles and has a period of 745 days. This period is variable, as a result of the strong perturbations on the satellite caused by the Sun.

Satellites I to V form a family which is at a mean distance of 500 thousand miles from the planet. All five rotate in the same direction as that of Jupiter itself. Satellites VI, VII and X have also the same direct motion and form another family which is at a mean distance of 4 million miles. Finally satellites VIII, IX, XI and XII form a third family which has a retrograde motion and is at a mean distance of approximately 14 million miles. The orbits of the satellites VI, VII, VIII, IX, XI and XII have high eccentricity ranging from 0·16 to 0·38 and inclinations ranging from 20° to 30°.

The orbits of the outermost satellites are so large that the gravitational pull from Jupiter is not strongly felt. Instead the gravitational attraction of the Sun produces such strong perturbations to their

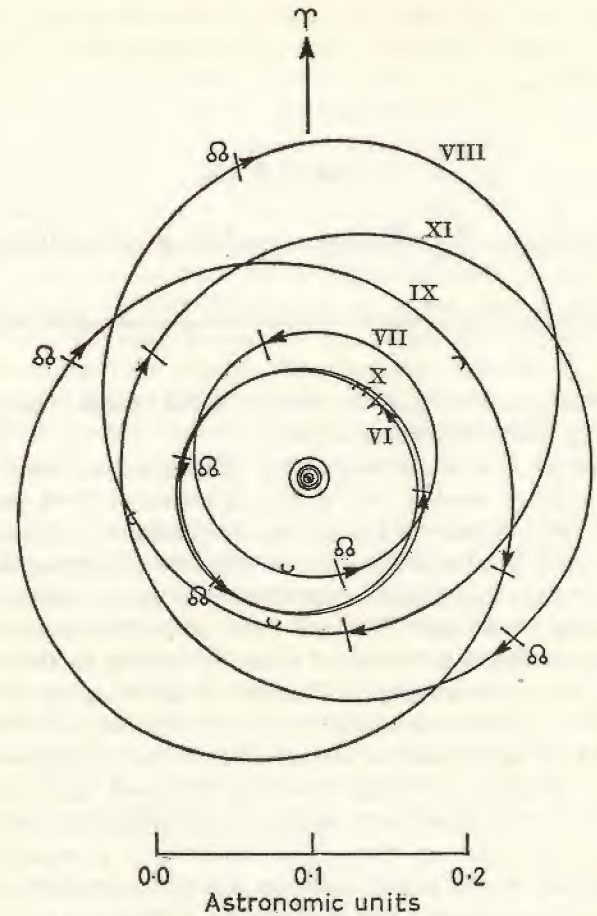


FIG. 40. Orbits of Jupiter's satellites.

motion, that the orbits cannot really be considered as being closed curves. The diameters of satellites VII, VIII, IX, X, XI and XII are only about 12 to 19 miles. These satellites can really be considered to be large meteorites or asteroids which have been captured by Jupiter and which may one day be lost.

The fact that the satellites can be divided into groups may be due to reasons related to their origin. On the other hand the orbit of each may have maximum stability at their particular distance from the planet, so that other satellites at different distances would be attracted gradually to form one or other of the families.

CHAPTER IX

Saturn, Its Rings and Its Satellites

Saturn is unique among all the celestial bodies known to us, because of the ring system which surrounds it.

This planet is at a distance of 886 million miles from the Sun, around which it revolves with a sidereal period of 29·46 years and a mean orbital velocity of 6 miles/sec. The inclination of its orbit to the ecliptic is 2° 29′ and its eccentricity is 0·056. Its mean diameter is 71,300 miles, that is nine times that of the Earth, while its mass and volume are 95 and 734 times those of the Earth respectively. Its mean density is 0·71 that of water. According to the distance from us, the apparent angular diameter of Saturn ranges from 15″ to 21″. The apparent magnitude varies not only because of Saturn's distance from us but also on account of how the rings appear to us. When the rings are seen edgeways from the Earth and are almost invisible and the planet is at opposition, its magnitude is 0·9, but when the rings open up they reflect almost twice as much light as that reflected by the planet itself, so that its magnitude, when at opposition, may reach −0·2. The albedo of Saturn is 0·42, which is a little less than that of Jupiter, but its photographic albedo is 25% less. This agrees with the fact that the planet is of a yellowish colour.

Saturn shows a considerable darkening at the limb and has some belts which are parallel to the plane of the rings. The belts are, in many ways, similar to those of Jupiter, but they are not so well marked nor as variable. In order to study the planet in different regions of the spectrum, photographs have been taken with various filters, and they give some information about the atmospheric envelopes of Saturn (Plate 26). The features of the surface disappear almost completely in infrared photographs, while photographs in yellow light show the equatorial belts to be bright and the polar

regions dark. In photographs taken in violet light, the equatorial belt becomes very dark and the polar cap almost disappears, while the darkening at the limb is much less than that in photographs in red light. The rings, when compared with the planet, appear very faint in the infrared and extremely bright in the violet.

The spots which occasionally appear on the disc of Saturn have been observed in order to determine the period of rotation of the planet. This period is different at various latitudes. At the equator it is 10 hours 14 minutes, but at higher altitudes, about 35°, the period reaches 10 hours 38 minutes. As in the case of Jupiter, the period is shorter near the equator, but on account of the difference in size of the two planets the equatorial velocity of rotation is different, being about 28,000 miles/hour for Jupiter and about 22,000 miles/hour for Saturn. In spite of this, the oblateness of Saturn is nearly 50% greater than that of Jupiter and is 1/9·5.

From observations it is possible to deduce that the visible surface of Saturn is gaseous and that the atmosphere is very deep. The surprising fact is the very low density of the planet. On account of the great distance of Saturn from the Earth, very few details can be observed on its surface. However it appears that in the clouds of its atmosphere, as in Jupiter, there exist considerable currents which may well be produced by interior heat in the planet. The evidence of the existence of this heat may be deduced from the fact that observations of the surface temperature show this to be −150° C., which is nearly 30° C. higher than the temperature due to solar radiation.

Occasionally disturbances appear to take place on the surface of Saturn. For example the large white spot can be mentioned which appeared in 1933 just below the ring and which a year later had disappeared, leaving in its place a white equatorial belt. At about this time the northern hemisphere, in which the white spot was located, had completely changed its appearance.

In the spectrum of the disc of Saturn are found the same bands as those in the spectrum of Jupiter although they are generally more intense. These bands, however, are not present in the spectrum of the ring, which has no atmosphere. The absorption bands due to methane are more intense on Saturn than on Jupiter, while the opposite is true for the bands due to ammonia. Furthermore there are several differences between the spectra of the two planets in the region from λ 7800 Å to λ 7950 Å. In the spectrum of Saturn there

exist well-defined bands which are due to one or more molecules and which have not yet been identified. These bands are much weaker in the spectrum of Jupiter.

There is no doubt that in the more external atmosphere of Saturn, ammonia and methane are found, just as in the atmosphere of Jupiter even if in different physical conditions. The difference in physical conditions may be due to temperature, for Saturn receives from the Sun less heat than Jupiter and its atmosphere is therefore colder so that all the ammonia must be solid.

The system of rings which surrounds Saturn has been the subject of many observations and theoretical investigations since the days of Galileo. Cassini was the first to discover that the ring is composed of two concentric rings, and much later the third ring was discovered, called the crape ring, which is like a veil.

The two main rings can be subdivided. The outer ring, called ring A, has a diameter of about 170 thousand miles and a width of about 10,000 miles; then follows the Cassini division which is nearly 3,000 miles wide. Ring B, which has a diameter of 143,000 miles approximately, and a width of about 16,000 miles, is much brighter than ring A, particularly at its external edge and reaches the brightness of the most luminous regions of the surface of the planet. Finally the crape ring C is not very bright and is almost transparent, so that the disc of the planet can be seen through it. The gap between the edge of this ring and the planet itself is of nearly 7,000 miles. The rings lie exactly in the equatorial plane of Saturn, and during the revolution of the planet around the Sun, the plane of the rings maintains the same slant.

Theoretical considerations have shown that the system of rings could not possibly consist of a continuous solid or liquid surface, because at the slightest disturbance a solid ring would have broken into pieces and fallen upon the planet, and a liquid ring would have divided into many parts. Even before any observational evidence was obtained, it was suggested that the stability of the ring was due to the fact that it was composed of a swarm of small satellites. This hypothesis was completely confirmed by both photometric and spectroscopic observations, which established that the variation of luminosity of the ring was a consequence of the various angles of its inclination and of the phase. When the slit of the spectrograph is pointed parallel to the major axis of the planet and of the ring, Doppler displacements can be measured which are produced by the rotation of the planet and of the ring. The absorption lines in the

spectrum, which naturally are those of the reflected solar light, appear to have different inclinations on the disc from those on the ring. The Doppler effect appears stronger at the internal edge of the ring and weaker at the external edge, suggesting that the system of rings has a much higher velocity in the internal than in the external part. This is a further proof that the rings consist of separate particles.

Measurements of radial velocities at various points of the rings show that, in their motion around the planet, they follow Kepler's third law, and that therefore they move as if they were satellites. The most external part of ring A has a rotational velocity of about 10·2 miles/sec., while the internal part has a velocity of about 12·4 miles/sec. A point on the equator of the planet rotates with a velocity of approximately 6 miles/sec. which corresponds to a period of 10 hours 14 minutes, which is the same value as that determined by observation of the spots on the surface of the planet. The lines in the spectrum of the ring appear to have a slant, as they should if each part of the ring had its own velocity.

The gaps, devoid of matter, between the rings can be explained by the hypothesis of meteoric constitution, taking into account the theory of Roche's limit (see p. 229) and the ratio of the orbits of the satellites. Assuming that the various parts of the ring are composed of fragments of equal size and are moving in circular orbits, the influence of the motion of the satellites on these parts of the ring could have produced Cassini's division between rings A and B and the division between B and C, in ratios which are comparable with those existing between some of the internal satellites.

Very interesting phenomena, which enlighten us on the physical properties of the system of rings, are observed when, about every fifteen years, the rings are seen edgeways and almost disappear. When the Earth is on the same plane as that of the ring, only its thickness can be seen, which is estimated to be no more than 12 miles. Another disappearance can also take place when the ring is edgeways with reference to the Sun, which in this condition cannot illuminate either the northern or the southern face of the ring. The disappearance which took place in June 1936, lasted a few weeks because the Earth remained for that amount of time on the plane of the ring. After that the ring reappeared for more than seven months, turning towards us the same face as before the disappearance. Towards the end of December, the Sun was on the plane of the rings and a further disappearance took place until the end of February 1937, when the

other face of the ring began to appear. A similar phenomenon took place in September 1950.

During the night of June 23, 1936, a very faint nebulosity enveloping the ring was observed (Plate 27), confirming the observations of a similar effect already obtained during the disappearances in 1907 and 1921. Along the extension of the shadow of the ring, projected on the disc of the planet at the time of the disappearance, irregular condensations were observed very like grains of dust in a beam of light.

Many questions concerning the constitution of the ring remain still unsolved, such as the contrast between the bright ring B and the darker ring C and the size of the fragments which compose them. Probably they are composed of meteorites, since a very fine dust would not be able to withstand the pressure of the solar radiation. Another uncertainty exists about the total mass of the ring which can be obtained from studies of the orbits of the satellites. In any case it looks as if the mass is very small, probably not much more than one millionth of that of Saturn.

Some information concerning the atmosphere of the planet and the constitution of its rings was obtained by Lyot in his studies of the polarization of the light from the planet. A polarization effect very similar to that shown by the clouds on Jupiter has been found in a whitish area which appeared in 1924 and which had the appearance of a very faint, thin cloud. The polarization curve for the ring is very different from that for the Moon and Mars. In the case of the inner ring the curve is similar to that for many minerals such as fragments of lava and of granite. From this it could be deduced that ring B is perhaps made up of pieces of matter of varying size. The phenomena which are observed on the external ring are very complex and the differences shown by the two loops are very conspicuous. Many more accurate observations will be required before these phenomena can be explained.

Saturn has nine satellites. The discovery of a very faint tenth has not been confirmed. The nine satellites, in order of distance from the planet, are: Mimas, Enceladus, Tethys, Dione, Rhea, Titan, Hyperion, Iapetus and Phoebe. The largest is Titan, which at mean opposition is of 8·3 magnitude, and the magnitudes of the others range from 10 for Rhea to 14·5 for Phoebe. The nearest satellite, Mimas, is at a mean distance of 113 thousand miles from the centre of Saturn and revolves around it with a period of 22 hours 37 minutes,

and it can reach a distance of 31,000 miles from the edge of the ring. The next four satellites follow in a group with periods ranging from 1 day 9 hours for Enceladus, to 4 days 12 hours for Rhea, and their distances range from 148,000 miles to 327,000 miles. After a rather large gap Titan is found at a mean distance of 759,000 miles, having a period of 15 days 23 hours and a diameter of about 2,600 miles. Titan is followed by Hyperion with a period of 21 days 7 hours. Beyond the latter there is another gap even larger than the previous one and then Iapetus is found at a mean distance of 2,210,000 miles and with a period of 79 days 8 hours. The inclination of the orbit of this satellite to the equator of Saturn is 13° 52′, while the orbits of all the other internal satellites are practically in the plane of the ring. After another even greater interval Phoebe is found, which is at 8,034,000 miles and has a period of 550 days 11 hours. This satellite, like the eighth and ninth of Jupiter, has a retrograde motion, and its orbit has a greater eccentricity and inclination than those of the other satellites of Saturn.

Only Titan shows a measurable disc, the angular diameter being 0″·6. At the time of transit of this satellite across the face of the planet, it appears dark when it is at the centre of the disc and then it becomes almost invisible when it reaches the edge. This indicates that the albedo of Titan must be about 0·5. Some very remarkable light variations of these satellites have been observed. Iapetus, according to whether it is west or east of Saturn, has a magnitude of 10 or 11·6. This phenomenon has been occurring since Cassini's days and it is interpreted as meaning that the satellite must always show the same side to Saturn. Tethys, on the other hand, is brighter when east than west of the planet. The other satellites too show noticeable variations of brightness.

The masses of the satellites can be calculated from the study of the perturbations produced on each other. Thus Titan has a mass 1·92 times that of our Moon; Dione, Tethys and Mimas have masses which are respectively $\frac{1}{70}$, $\frac{1}{120}$ and $\frac{1}{2,100}$ times that of the Moon. The internal satellites have masses which are very small when compared with their brightness and therefore must have an albedo greater than that of Saturn and a very low density.

CHAPTER X

Uranus and Its Satellites

Uranus is the planet discovered by Herschel on March 13, 1781, and called by him 'Georgium Sidus'. Its average distance from the Sun is 19·19 A.U., equivalent to 1,800 million miles. The revolution around the Sun is completed in 84 sidereal years with a velocity of 4·2 miles/sec. The orbit described by Uranus has an eccentricity of 0·047 and an inclination to the plane of the ecliptic of only 46′, while the equator of the planet is inclined 98° to the plane of its orbit. The mean diameter of Uranus is about 31 thousand miles and its apparent angular diameter ranges from 3″·4 to 4″·2. Its mass and volume are respectively 14·66 and 64 times those of the Earth, while its density is 1·27 times that of water. The rotation of the planet around its axis which is retrograde, like that of its satellites, takes place in 10 hours 42 minutes. At mean opposition its magnitude is 5·74. The albedo (0·45) is very similar to that of Jupiter and Saturn, suggesting that its constitution, as is confirmed by its spectrum, is similar to these other two planets. The visible surface is marked by faint belts similar to those existing on Jupiter.

In the light variations of Uranus, which are wholly due to changes in its distance, a periodicity of 42 years and an amplitude of 0·3 magnitudes have been detected. This periodic variation depends partly on the oblateness of the planet (1/14), partly on the fact that its axis of rotation lies almost on the ecliptic, and partly on its period of rotation. During a complete revolution of Uranus round the Sun, the disc of the planet, as seen from the Earth, is twice limited by the circle of the equator and twice by the ellipse of one of the meridians. Another periodic variation, probably due to the physical constitution of the planet, seems to be superimposed on the previous one.

The spectrum of Uranus shows intense bands in the green, in the yellow and in the red. These bands are similar to those of Jupiter

and Saturn but more intense. Their intensity in the yellow and red is such as to obscure almost completely these colours in the spectrum, and may partly explain the greenish colour of the planet.

The bands in the spectrum of Uranus are due to absorption by ammonia and methane. The measured temperature of Uranus is −185° C. against −210° C. obtained from theoretical calculations. Ammonia must be completely frozen, thereby leaving the atmosphere transparent to a great depth, and this may explain the considerable intensity of the bands of methane.

Uranus has five satellites. Ariel and Umbriel were discovered by Lassell; Titania and Oberon by W. Herschel; and Miranda was discovered in 1948 by Kuiper. Their distances from the planet range from 119,100 miles to 364,500 miles, and their periods are between 2 days 12 hours for the nearest satellite and 13 days 11 hours for the furthest. At mean opposition their magnitudes range from 14 for Titania to 16 for Umbriel. The dimensions of the satellites are probably comparable to those of the inner satellites of Saturn. All the orbits, which are almost circular, lie in a plane which coincides with that of the equator of the planet. This plane, however, has an inclination of 82°·2 to the ecliptic, namely, since the motion of the satellites is retrograde, of 97°·8. Because of this and according to the position of the planet in its orbit, the orbits of the satellites will be seen from the Earth either edgeways, or face on, or at an angle. In 1924, when the orbits of the satellites were seen edgeways, the satellites appeared to be moving in a straight line, and this will happen again in 1966. In 1903 and in 1945 the orbits of the satellites appeared as circles.

CHAPTER XI

Neptune and Its Satellites

The circumstances of the discovery of Neptune are well known. The fact that it was possible to predict not only the existence of an unknown planet beyond Uranus, but also its position, was a real triumph for celestial mechanics.

Neptune is at a distance from the Sun of 30·07 A.U., equivalent to 2,800 million miles. It travels around the Sun in an orbit which is almost circular, at a mean velocity of approximately 3·3 miles/sec. in 164·8 years.

The orbit has an inclination of 1° 47′ to the ecliptic, while the inclination of the equator of Neptune to the plane of its own orbit is 29°. The mean diameter of the planet is about 33 thousand miles and its apparent angular diameter is on average 2″·6.

The mass of Neptune, which can be determined fairly accurately either by means of its satellites or by its effect on Uranus, is 17·26 times that of the Earth, while the volume is 60 times that of the Earth. The density is 2·2 times that of water, its oblateness is 1/45 and the albedo is 0·5 or perhaps even greater. When at mean opposition its magnitude is 7·65. Since no markings are visible on the disc of the planet, its rotation can be determined only by variations in its brightness or by spectroscopic means. At present the results obtained would point to a rotation of 15 hours 48 minutes.

Spectroscopically both Uranus and Neptune are very similar, although the absorption bands, particularly those in the red, are much more intense in the spectrum of Neptune. Both ammonia and methane are present also in this planet. The intense bands which are observed in the spectrum of Neptune, mean that on the planet there must exist a layer of gas much thicker than the whole atmosphere of the Earth. Methane, in spite of its low boiling point, must be almost condensed on Neptune. Estimating the depth of the

gaseous layer on the surface of the planet to be 6 miles, at a pressure of one atmosphere, the pressure due to this layer would be approximately equal to 20 inches of mercury with a temperature limit of −165° C. This, according to Russell, could be reduced to −180° C. if hydrogen was very abundant. The solar radiation maintains a mean temperature of −220° C. on Neptune. To be able to explain this difference in temperature of the surface of the planet it is suggested that either there must still exist a certain amount of internal heat or that the gases on the planet store heat.

In recent years the knowledge of the planetary atmospheres, which had always presented a serious challenge to astronomers, has made considerable progress, with the help of other sciences.

Two satellites of Neptune are known. Triton, which is 220,000 miles from the planet, has a magnitude of 13·6. Its orbit is almost circular with a period of 5 days 21 hours and has an inclination of 40° to the orbit of the planet. The motion of Triton is retrograde and its diameter is estimated to be approximately 2,800 miles.

Nereid, the other satellite, which was discovered by Kuiper in 1949, has a magnitude of 19·5. It revolves around Neptune with a period of about one year and has a diameter of about 186 miles.

CHAPTER XII

Pluto

The last planet of the solar system so far known is that discovered not long ago (1930) by Tombaugh at the Lowell Observatory, Flagstaff, Arizona. On March 12 of that year, the planet was near the star δ Geminorum. Its longitude was in agreement with that predicted by Lowell. He had calculated the theoretical position of a possible planet beyond Neptune, which could account for the small variations observed in the motion of Uranus. Neptune could not be used to explain this since it had not been observed for a long enough time to give a sufficiently accurate mean orbit. The search for this new planet was more difficult than in the case of Neptune, both because of the uncertainty of the predicted position and because of its brightness. In fact at the time of the discovery Pluto was found to be only of the 15th magnitude.

In spite of the great distance of Pluto, and hence its very slow motion, the main characteristics of this new member of the solar system are known (Plate 28). Pluto is at a distance of 39·5 A.U. from the Sun. On account of its orbit, which has a very high eccentricity (0·3), its actual distance from the Earth ranges from 4,600 million miles to 2,800 million miles. At its maximum distance, therefore, Pluto is much further than Neptune, but at its minimum distance it is almost half an A.U. nearer to the Sun than Neptune. The distance predicted by Bode's law is almost twice the actual mean distance, and therefore it can be said that this empirical law does not hold either for Neptune or for Pluto. The latter takes about 248 years to travel round its orbit at a mean orbital velocity of about 2·9 miles/sec.

In the coming years, as Pluto is coming nearer to the Earth, reaching the perihelion in 1989 (Fig. 41), it will be possible to obtain better observations. Meanwhile, from the observations so far available and from the position of the planet measured on photographic

plates which were obtained before its discovery as far back as 1914, the elements of its orbit have been calculated. The inclination of the plane of the orbit to the ecliptic is 17°, which is greater than for any other planet. As seen from Pluto, the Earth would be enveloped by the light of the Sun, the maximum elongation of the Earth being only 2°.

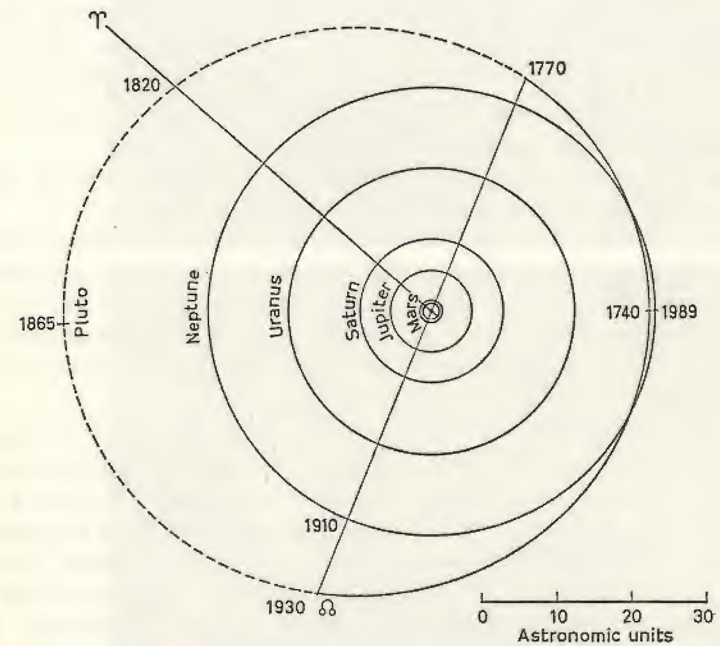


FIG. 41. Orbits of the planets around the Sun.

The mass of Pluto has been calculated by various methods such as by using the perturbations produced by it in the orbits of Jupiter, Saturn, Uranus and Neptune, or by means of its apparent magnitude, or again by means of its apparent diameter. The differences between the actual and the computed positions of Jupiter and Saturn, which could be attributed to the effect of perturbations produced by Pluto are very small; they are in fact of the order of the errors of observation. This at least proves that the mass of this new planet cannot be very large.

The prediction of the existence of Pluto by Lowell has given rise to speculations as to whether the discovery of this new planet was purely fortuitous. Kourganoff has analysed the complex work of

Lowell and he has calculated again the perturbations produced by Pluto in the orbit of Uranus, and has come to the conclusion that the discovery was neither purely accidental nor was it solely the result of the application of the principles of celestial mechanics. Several factors have contributed to the success of the discovery. These were as follows:

1. Greater accuracy, in modern times, in the observations of Uranus than was possible before 1780, when the perturbations were much stronger because of the relative nearness of the two planets.

2. The precise theory of Leverrier-Lowell which had formed the basis for the discussion of both the ancient and new observations of Uranus in a practical and efficient manner.

3. The accurate search for the trans-Neptunian planet at the Lowell Observatory and the enthusiasm of Lowell.

Kourganoff concludes that certainly the discovery of Pluto could not be due to pure chance, but that its existence was predicted theoretically by Lowell as far back as 1915. Pickering in 1919 had also predicted theoretically the existence of a trans-Neptunian planet with a more empirical method and finally this planet was discovered by Tombaugh by means of photography.

The determination of Pluto's mass, by studying its action upon Neptune, presents also great difficulty when the observations made after the discovery of Neptune in 1846 are analysed. However it is possible to fix a value equal to half that for the Earth as an upper limit for the mass. In order to obtain a more accurate value, based on the theory of perturbations, it is necessary to wait for at least another century of observations of the motion of Neptune. A mechanical integration carried out recently by Brouwer and Wylie at Yale University for Uranus and Neptune has suggested that the mass of Pluto is probably between that of Venus and that of the Earth.

There will always be some difficulty in the calculations because of the relation of the periods of revolution, which for Uranus, Neptune and Pluto are nearly in the ratio of 1 : 2 : 3. Some of the perturbations of Uranus produced by Neptune have about the same period as those produced by Pluto. A small error in the evaluation of the first can well modify the others to such an extent as to lead to erroneous values for mass of the new planet.

From the apparent magnitude of Pluto, and if its albedo were known, it would be a simple matter to determine the diameter. The magnitudes, both visual and photographic, have been determined as

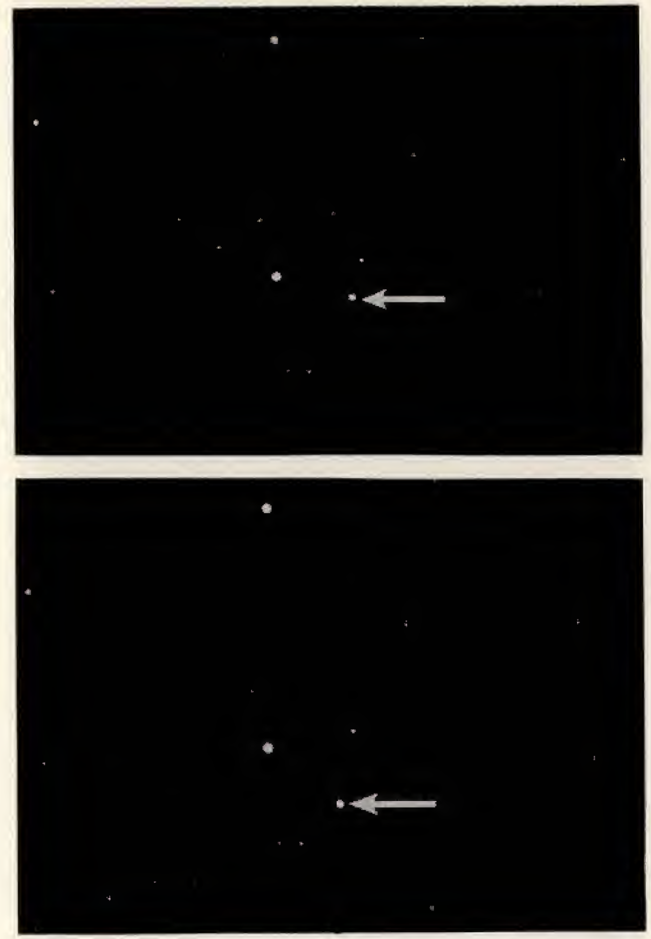


Plate 28. Pluto photographed by the 200-inch telescope Mt. Palomar. Note the change of the planet's position in a period of 24 hours

being 15 and 16 respectively. As for the albedo we can only surmise that it is of the order of the other planets, namely between 0·1 and 0·5. If these values are adopted, the diameter is found to be probably between 2,000 miles and 5,000 miles and the volume between 0·02 and 0·40 times that of the Earth. When the density is assumed to be of the order of that of Uranus and Neptune, namely 1·5 that of water, then the upper limit for the mass of Pluto would be $\frac{1}{10}$ of that of the Earth.

The necessity of knowing the albedo of Pluto can be eliminated if its apparent diameter can be measured. The upper limit for the angular diameter had been estimated to be of the order of 0″·5 at the distance where the planet was at the time of its discovery. In the year 1950, Kuiper was able to obtain a direct measure of the diameter of Pluto, with the 200-inch reflector at Mt. Palomar. He used for comparison small artificial discs placed at the focus of the telescope, and he was able to vary their brightness, colour and diameter. These observations, made in March 1950, when Pluto was at a distance of 35·6 A.U., gave as a result a diameter of 0″·23 with a mean error not greater than 0″·01. The value for the albedo of Pluto is then 0·17, and therefore its diameter is 0·46 times that of the Earth, namely between that of Mars and that of Mercury.

The temperature of Pluto, at the mean distance from the Sun, must be of the order of —230° C., so that the gases of its original atmosphere must be mostly liquefied or solidified. In contrast to Mercury, Mars, and the Moon, Pluto has a colour index only slightly different from that of the Sun. This leads to the hypothesis that its rocky surface is invisible to us. If the value of the diameter determined by Kuiper is confirmed, then the volume and the mass would be only 0·1 of the respective values for the Earth, and this makes its discovery a remarkable feat. With such values for mass and volume, the density of Pluto would be equal to that of the Earth. On the whole it would appear that the dimensions of Pluto are rather small, comparable in fact to those of the minor planets. Perhaps other similar planets at even greater distances may exist, which would extend still further the limits of the solar system.

CHAPTER XIII

Comets, Meteors and Meteorites

Comets, meteors and meteorites complete the family of celestial objects which are ruled by the Sun and which are part of the solar system. Although all these objects cannot be classified either as stars or as planets, which are the subject of this book, nevertheless, according to the latest information, the relation between them and the planets is so close that mention of them ought to be made.

The appearance of comets is well known. They may be very bright and visible to the unaided eye, or very faint and detectable only by photography and the larger telescopes. The orbits of comets can be divided into two groups according to whether the orbits are very nearly parabolic or elliptical. In the latter case they are periodic (fig. 42). In some cases the ellipse can be very elongated, and then the two groups may become confused, since it is not easy to distinguish between an ellipse and a parabola when the periods are very long or the observations are not accurate enough.

Of all the comets discovered since 1900, forty-eight appear to have parabolic orbits. Of the remaining number, thirty-three have an eccentricity slightly greater than one, and thirty have an eccentricity smaller than one. For those which have an eccentricity greater than one it would be reasonable to suppose that the comets come from interstellar space, to which they return, while those which have an elliptical orbit belong to the solar system. This is rather an important question because the answer to it would enable us to decide whether these objects, so mysterious both in their appearance and constitution, do belong to the solar system or are visitors from interstellar space.

The present evidence seems to point with greater probability to the first of these two possibilities. Since the whole solar system moves in space, we ought, in our motion, to meet some comets which follow

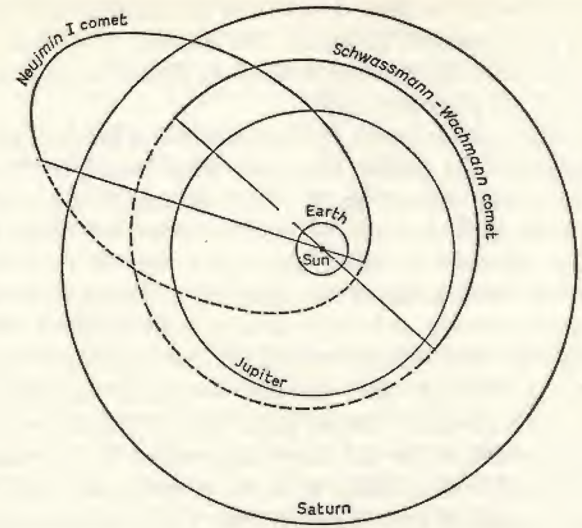


FIG. 42. Orbits of two periodic comets.

hyperbolic orbits. Orbits of this type, calculated for some of the comets in the neighbourhood of the Sun, are osculant orbits. Calculations show that in these cases, the comets, having passed near to Saturn and Jupiter, have undergone an increase in velocity on account of the planets' attraction, so that the hyperbolic character of such orbits must be due exclusively to this cause. In the majority of the cases studied, the original orbits, at a great distance from the Sun, were certainly elliptical. In the other cases it can be assumed that they were very elongated ellipses, so that there is no record of a comet approaching the Sun and describing a hyperbolic orbit. The few hyperbolic orbits observed must therefore have been produced by planetary perturbations during the years when the comet was approaching perihelion. It would appear, therefore, that the comets are members of the solar system and probably were born at the same time as it. There is not enough evidence to state whether the comets, which when near the Sun follow hyperbolic orbits, are lost to the solar system, or in some way come back to it. If the comets which are non-periodic never return, then either their number must decrease in time or they must be replaced by others, by means of some kind of process of formation within the solar system.

The planes of the orbits of comets, unlike those of the planets, have inclinations which can vary over a large range. About half of

the comets move in the same direction as the planets, while the other half move in an opposite direction. The majority of comets move in planes which have an inclination which is almost at right angles to the plane of the planetary orbits.

The periodic comets can be divided into several families, according to the length of their period, which can range from 5 to 50 years or even more. A well-defined family, which belongs to a group having a short period between 3 and 8 years, is known as Jupiter's comet family. The aphelion of this group is not very far from Jupiter's orbit and one of its nodes is very close to it. About 40 comets can reach a mean distance of 22 million miles from Jupiter's orbit.

Although the short-period comets are not distributed systematically like the asteroids, they certainly are under the influence of Jupiter to such an extent that its perturbations reduce the length of their periods until, in the end, they are captured by the planet. The type of the final orbit depends upon the direction and velocity with which the comets had approached Jupiter. For various causes, either external or internal, the orbits of these comets may undergo notable variations. Thus the Pons-Winnecke comet, first discovered by Pons in 1819, re-discovered by Winnecke in 1858 and since then observed regularly every six years, shows some progressive variations in the elements of its orbit. The inclination has doubled from 1819 to 1933 and its minimum distance from the Sun has changed from 0·77 to 1·10 A.U. These changes have occurred because the motion of the comet is almost in resonance with that of Jupiter. The comet performs two revolutions to one of Jupiter.

Some of the periodic comets were never seen again at the time when they were due to be at perihelion. It is likely that at least some of these losses are due to a disintegration of the comet. In the particular case of the Biela's comet the disintegration has actually been observed. This comet was discovered in 1722. It had a period of 6 years and 9 months and was observed on several of its returns. When at perihelion in 1846 it was seen to divide into two parts, which continued their motion side by side for more than three months at a distance of about 155,000 miles. Each developed its own nucleus and tail, and in 1852 they appeared to be further from each other. Since then they have never been seen again, not on account of perturbations, but rather because their brightness had diminished considerably or had possibly disappeared altogether.

Obviously when the comet passes near to bodies of very large mass such as the Sun and Jupiter, its nucleus is subject to strong

disintegrating actions, so that the part of the comet which is facing them is torn away from the rest, unless there is enough material to keep it together. In order that a swarm of particles or a cloud of gas should remain unaltered under the action of a heavy mass, it must have a given density which it is possible to calculate. This density is found to be three times as large as the density the mass would have if it were distributed over a volume whose radius is equal to the distance between the large body and the comet. When the density of the comet reaches values below the critical value, which varies rapidly with the distance between the comet and the attracting body, then the comet disintegrates.

The evidence of these observations and the spectroscopic observations, leads us to the conclusion that comets are not a solid body, but rather they consist of extensive gaseous clouds which surround a conglomeration of small bodies, such as asteroids and meteorites. If we observe the nucleus of a comet under high magnification, the image still appears like a star image enveloped by dense vapours. The 'coma' surrounding the nucleus is a very large luminous envelope which increases in brightness nearer to the nucleus and can reach dimensions comparable to Jupiter if not more. The 'tail' is composed of very tenuous matter, so much so that stars can be seen through it without any loss in brightness. The tail can be compared to the beam of light of a powerful searchlight which illuminates the path of the comet. Although the direction of the tail is partly influenced by the motion of the comet, the tail is always directed in an opposite direction to that of the Sun (Plates 29, 30).

The coma is continued into the tail, which, like a plume of smoke, can have various angles to the direction of its motion on account of the combination of its own motion and the repelling force produced by the sunlight. This repelling force due to the pressure of light has a great influence on the matter of which the tail is composed, namely corpuscles and gases. The pressure of light is proportional to the intensity of the light and to the dimension of the surface which absorbs or reflects the luminous radiation. The pressure exerted per unit area, upon which the radiation falls at right angles, is $P = I/c$, where I is the intensity of the beam of light and c is the velocity of light, assuming that the radiation is transmitted in a vacuum. Since we know the solar constant, which is about 2 calories, we can calculate the value of the pressure exerted on the Earth by the light of the Sun. If we assume that the pressure exerted by a beam of sunlight with a cross-section of one square metre on a black body of an area

of one square centimetre, at the distance of the Earth from the Sun, is half a milligramme, then the pressure exerted on the whole of the Earth will be approximately 20 thousand metric tons.

Both the forces of attraction and of repulsion vary in inverse proportion to the square of the distance from the Sun. For a given body then, their ratio is a fixed value which is directly proportional to its surface A and inversely proportional to its mass m. The ratio of these two quantities in the case of a sphere of radius r and density d is: $A/m = 3/rd$. Even for the smallest planet this quantity is very small and therefore the pressure of radiation can be neglected, but this is not so for extremely small particles. Their mass decreases more rapidly than their area and the repulsion due to the pressure of radiation can be equal to or even greater than the gravitational force.

At a temperature of 0° C., two spherical bodies radiating as black bodies and having a density of 10 g/cm^3 and 4 mm. radius do not exert any attraction or repulsion on each other in the interstellar space. In the case, however, of bodies having a smaller radius, the force of repulsion is greater than that of attraction. For particles having a radius of the order of 1 μ, the force of repulsion is one million times greater than that of attraction. The light of the Sun exerts a repelling force on dust particles having diameters of about 0·2 μ or 0·3 μ, which is nearly ten times that of attraction of the Sun. Indeed it may be even greater upon luminous molecules of gas which absorb energy from the light of the Sun.

It is not known by what mechanism these particles are emitted or even ejected from the nucleus, as has been observed sometimes in the tails of the comets. The initial velocities of these particles, which often are several miles per second, are greater than those due to a simple expansion of gases in a vacuum. In such cases it is plausible to consider it as a real explosive process, due either to the solar radiation which is growing in intensity when the comet approaches perihelion, or to latent forces existing in the head of the comet and which may be brought about by the same cause.

In order to explain the acceleration of matter in the tails of comets, particularly in those tails which are long and straight and have a filamentary structure, another hypothesis has been put forward. It is known that during periods of high activity some of the disturbed regions of the Sun emit a corpuscular radiation which consists of electrons and positive ions in equal number, or what is known as 'plasma'. When the plasma reaches the neighbourhood of the Earth, it produces magnetic storms in the Earth's magnetic field. Something

like this may well happen when the corpuscular radiation reaches the comets, in the sense that it may produce the acceleration of matter which is observed in the tails. Actually a phenomenon of this type was observed in 1943 in the tail of the comet Whipple-Fedtke (1942 g). The phenomenon was repeated after one rotation of the Sun with reference to the comet, when the disturbed region of the Sun was towards the comet.

The strange helicoidal structure, which sometimes is observed in the tail of a comet, suggests the possible existence of magnetic fields in these objects, which may be the cause of the observed acceleration of matter. There also appears to be some physical relation between the phenomena shown by comets, such as variation of luminosity and the solar phenomena. For some comets (1936a, 1948a and 1948g) it has been shown that the greater activity of the Sun, displayed in sunspots and other phenomena, is responsible for the excitation of the gases emitted by the nuclei. Moreover it has also been observed that the luminosity of comets is higher at low heliocentric latitudes.

The whole of the material which constitutes the tail of a comet moves in parabolic orbits and is therefore lost in space. The material forming the comet is gradually disappearing and this would explain why some short-period comets have disappeared completely. Even the well-known Halley's comet, which in 1910 had a very long and bright tail, appears, in the last thousand years or so, to have decreased in brightness by at least two magnitudes.

The mass of a comet does not seem to produce any measurable attraction upon the planets, not even when it comes relatively near to them, therefore it is not possible to reach any conclusion about the total quantity of matter existing in the comets. One thing is certain, that the amount of matter contained in about a thousand cubic miles in the tail of a comet, is less than that contained in a cubic inch of air of our atmosphere.

By means of the spectroscope it is possible to obtain some indication of the physical constitution of a comet by studying their spectrum and its variations. The continuous spectrum shows the absorption lines of the solar spectrum, since the light is reflected sunlight. In addition in 1864 Donati discovered the existence of luminous bands which later Huggins identified as being produced by carbon compounds. The most intense are those due to molecules C_2, those in the violet are bands due to CN and CH. Other bands due to Co, N_2, NH and OH are also present. These last bands were discovered by Swings in 1940, in the ultraviolet spectrum of the head

of the comet Cunningham. When a comet is distant from the Sun the main bands are due to CN, but as it approaches the Sun the bands of C_2 and CH increase in intensity. Three bands of C_2, known as 'Swan bands', are the most conspicuous in the visible region of the spectrum and the heads of these bands are at λλ 4737 Å, 5165 Å and 5635 Å. The temperature required for these bands to appear is 2,700° C., while a much lower temperature is sufficient for the CN bands. It follows, therefore, that it is not possible to think of a thermodynamic equilibrium in the atmosphere of comets. In some comets the isotope C13 is found, but the abundance of this element varies from comet to comet. In spectra of comets which are within the orbit of Mars, the bands of CO and N_2 are found and when they are at the distance of Venus from the Sun, the yellow light of sodium appears and dominates the spectrum. The spectrum of comet 1882 II at perihelion showed several lines due to atoms of sodium, iron and perhaps also of chromium and nickel.

The molecules which form a comet may absorb a great quantity of ultraviolet light until they break up. When the ultraviolet radiation from the Sun is very intense, then the comet will break up rapidly until the atomic lines, produced by the evaporation of the solid materials of the nucleus, appear.

The molecules of CO and N_2 seem to separate less easily than those of C_2, CH and CN, and these latter, which emerge from the coma, disappear very quickly. The molecules of CO and N_2, which have a longer life, are scattered in the tail of the comet of which, indeed, they are the sole components. When the comet comes even nearer to the Sun, then these molecules too break up and the apparent magnitude of the coma decreases. This happened to Halley's comet when it last appeared in 1910.

According to Bobrovnikoff, it is important, in the study of the physical conditions of comets, to establish the distribution of molecules in their various parts. The molecules of CH and CH_2 are found mainly in the immediate neighbourhood of the nucleus, while the molecules of C_2, CH, OH and NH are distributed throughout the coma and the brightness of the comet is due to the luminescence of the molecules of C_2. Comets which have very bright tails show also a continuous spectrum. The atmosphere of the comets is produced, according to Swings, by the release of gases contained in the meteoric stones which constitute their nuclei; and the molecules we observe are the result of photo dissociation of the gases, accompanied, or followed, by ionization.

Further observations of the appearance and evolution of the various bands, as well as of the variations of excitation which atoms and molecules undergo in relation to the distance of the comets from the Sun, may well give valuable information concerning the change in luminosity when the comets are at perihelion.

Short-period comets appear to have characteristics of a more advanced age than the others. They do not have very conspicuous tails, their brightness is not very great and their spectra show only a few faint lines superimposed on the continuum produced by the reflected sunlight. The disintegrating force of the Sun is very strong when the comets are at a perihelion which is relatively near to the Sun and this explains why the comets may break up in fragments. The nuclei of comets must have dimensions which are relatively rather small. From comets which have come near enough to us to allow observations to be made, it would appear that the nuclei have a diameter of a few miles. When comets disintegrate, all that is left is a swarm of particles, and it is natural to suggest that the nucleus is made up of these particles and surrounded by various gases at very low pressure.

There are, so far, no plausible hypotheses on the origin of comets and how they could have been formed either at the time of formation of the solar system or during its evolution. Their form, their distribution, the position of their orbits and the absence of preferential direction of motion do not give any help in trying to understand how these bodies have come to be part of the solar system, whether they were part of the Sun or of some planet. In the present state of our knowledge all we can say is that it is possible that comets are members of the solar system and have characteristics which are common with the asteroids and the meteors and that, as they break up in passing near the Sun, they leave behind showers of meteors.

This theory, often suggested by astronomers, was supported by Schiaparelli following his observations and his theoretical deductions and calculations. According to him showers of meteors are the product of the disintegration of comets and consist of very tiny particles which they have left behind in their orbit. The disintegration is due to the force that the Sun and the planets exert upon the rarefied matter of which the comets are composed.

Schiaparelli investigated the transformations which an aggregate of cosmic matter undergoes when it comes within the sphere of influence of the Sun. He showed that for any cloud of rarefied matter either continuous or discontinuous, the law of attraction determines

the transformation of that mass into a very long thin stream bent into a curve which, in the neighbourhood of the Earth, differs very little from a parabola and, in any case, is very similar in general to an elongated conic section. The number of such showers of meteors can be very great, and the particles which make up these showers are so scattered that their orbits may well cross each other and change course.

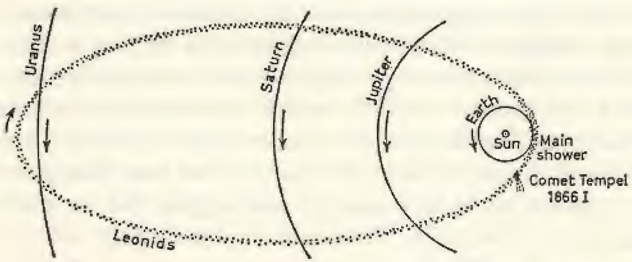


FIG. 43. Orbit of Comet Tempel 1866 I and of the meteor shower Leonids.

A comet, after perihelion, becomes gradually more diffuse and when it happens to pass near a planet may be so violently affected as to divide and break. Some particles may even be diverted into a new orbit and so become sporadic meteors. As a proof of this theory Schiaparelli calculated the orbit from the position of the 'radiant' and from the speed of the shower of meteors called Perseids because it appeared in Perseus in 1866. The elements of the orbit so obtained showed a very significant coincidence with those of comet 1862 III, which had a period of revolution of 121 years. The encounter between the meteor shower and the Earth takes place at a velocity of 38 miles/sec.

A similar calculation for the 'Leonids', which in November 1866 gave rise to a spectacular shower, shows that the elements of the orbit are the same as those for comet 1866 I, discovered by Tempel, which had passed its perihelion in January of that year and which had a period of revolution of 33 years (fig. 43). In this case the encounter between the meteors and the Earth takes place with a velocity of 45 miles/sec., which is nearly the maximum possible velocity attained by meteors in their fall. This last discovery dispelled any doubt on the relation existing between comets and meteors as well as on the nature of the orbits that the latter describe in space.

The splitting into two and the subsequent disappearance of Biela's

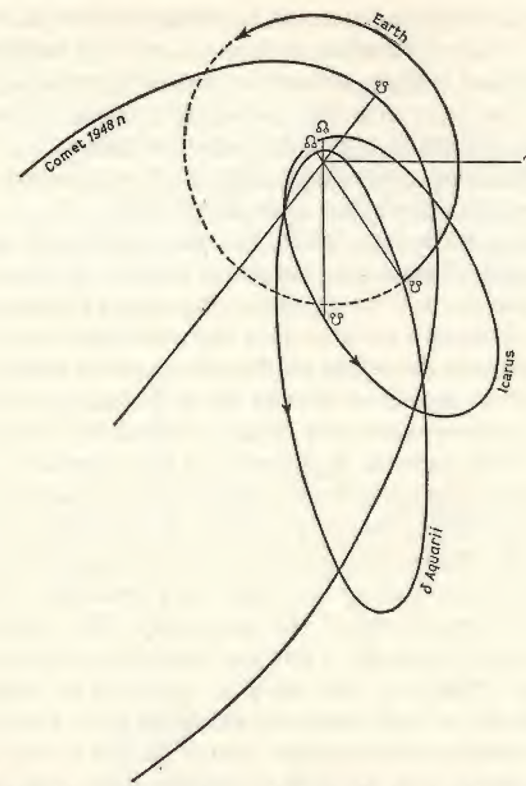


FIG. 44. Orbit of the meteor shower δ-Aquarids, from radio observations. The orbits of Comet 1948n and of Icarus are also given. (A. Lovell.)

comet was less mysterious when it became possible to identify this comet with the 'Bielids' which produced the great showers of 1872 and 1885.

So far we know the link between only about a dozen comets and the meteor showers produced by them.

In recent years great interest has developed in the observation and study of meteors, particularly in the United States. The investigations are not limited to the determination of the radiant, the appearance, height and velocity of meteors, by means of photographs taken simultaneously at various stations. They also extend to the study of their physical constitution, by means of photographs of their spectra, obtained with special instruments. At the same time spectroscopic studies on meteorites are also carried out in laboratories.

The average height of meteors from the surface of the Earth appears to be about 60 miles, irrespective of their brightness, but for the larger and brighter meteors, or fire-balls, the height may be as little as 25 miles or even less. Generally speaking the initial and final heights of meteors depend upon the velocity with which they meet the terrestrial atmosphere. Meteor showers usually appear higher in the atmosphere than sporadic meteors.

Special cameras, having a field of 60°, may record only one meteor after 100 hours of exposure, but when showers like the Perseids occur, then the rate may be as high as one meteor for every 5 hours of exposure. From two stations of the Harvard Observatory 25 miles apart, cameras with fast lenses are directed in such a way as to point to a region of the sky about 50 miles above the surface of the Earth. Following a predetermined time-table, photographs are taken simultaneously at both stations. As a result the same meteor is recorded by both stations. The cameras are equipped with an occulting shutter which has the effect of breaking up the trail of the meteors twenty times a second. This enables the observer to calculate with accuracy the velocity of the meteors and how they decelerate when they penetrate the denser layers of our atmosphere. The deceleration is not very great, it is generally a little less than the acceleration due to the terrestrial attraction. The velocities obtained by these photographic methods are well below the parabolic limit, and it appears that these meteors have a similar motion to that of the asteroids which come very close to the Earth. Asteroids, which reach perihelion at a distance of about 0·6 A.U., meteors and short-period comets, all appear to have a great similarity in the elements of their orbits.

In 1949, Baade, with the 48-inch Schmidt at Mt. Palomar, discovered an object which has been classified as an asteroid, but which has characteristics very similar to a comet or a meteor. Baade, who twenty-five years earlier had discovered Hidalgo (see p. 277), obtained some photographs of a region of the sky in the neighbourhood of Antares with an exposure of one hour, and detected on the plate a long trail which had obviously been made by an object which was travelling fast and relatively near to the Earth. It was thought to be another member of the family Apollo, Adonis and Hermes. Further observations enabled its orbit to be determined, and this appeared to have such a high eccentricity (0·83) as to suggest the possibility that it was either a comet or even a meteor on account of its small dimensions. The diameter of this object was barely a mile and no trace of coma was visible in the photograph. Baade considered this

object to be an asteroid and he called it Icarus (fig. 45). This asteroid is the object which, as far as it is known, comes nearest to the Sun, the minimum distance being 0·19 A.U.; indeed it is the first asteroid known which crosses Mercury's orbit, an occurrence which is not unknown in the case of comets and meteors. Having an orbit with such an eccentricity, its temperature ranges from 550° C., when nearest to the Sun, to a temperature below zero at its greatest distance from the Sun which is beyond the orbit of Mars. Icarus comes as near as 0·04 A.U. from the Earth near the descending node of its orbit and reaches a magnitude of 12·5.

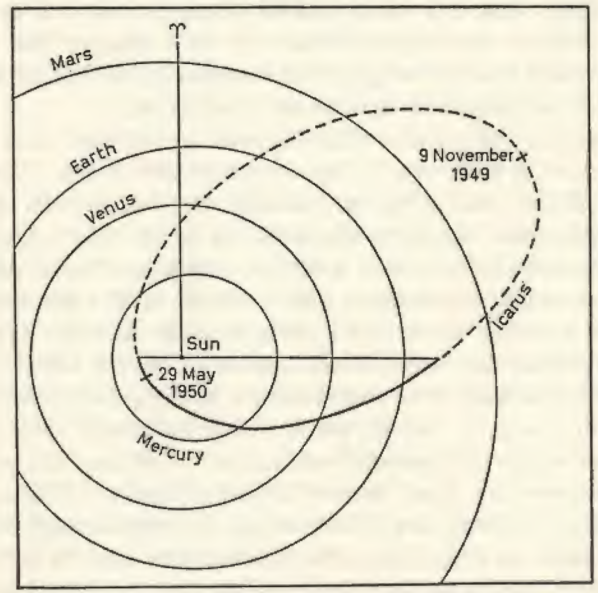


FIG. 45. Orbit of the asteroid Icarus.

The great progress made in recent years in the study of the orbits and velocity of the meteor showers and sporadic meteors is mainly due to the development of radar-astronomy and new types of very fast cameras. These studies are not only of great importance for astrophysics but also for geophysics in the study and understanding of the structure and composition of the upper atmosphere.

The cameras used at the various stations of Harvard Observatory are known as 'Super-Schmidt'. They consist of two thick hemispheric glass shells and a compound correcting plate. The aperture of these

cameras is 12 inches and the focal length is 8 inches, giving a field of 55° with an effective focal ratio f/0·85.

Meteors are being studied by using radar methods, as follows. Meteors reflect the pulses emitted by a transmitter, giving rise to echoes. By measuring the time interval between the transmissions and the reflections we obtain information about the presence and motion of the meteors. The method is extremely sensitive and reveals many more meteors than can be observed either visually or photographically and, what is more, it can be used in daytime as well as at night. The radar type of observation is however satisfactory only in the case of meteors having a path almost at right angles to the radar beam, while the visual and photographic methods are satisfactory only in the neighbourhood of the radiant of the meteor shower. From these investigations it has been found that the velocity of meteors is not greater than about 50 miles/sec.

The velocity of meteors with reference to the Sun must not be greater than 26 miles/sec. if they are permanent objects of the solar system. If they had a greater velocity they would then describe hyperbolic orbits and soon would be out of the solar system. The Earth moves in its orbit with a velocity of about 19 miles/sec., then if the meteor follows the Earth with a velocity of 26 miles/sec. it will overtake it with a velocity of 7 miles/sec.; on the other hand, if it comes towards the Earth it will appear to have a velocity of 45 miles/sec. This velocity is also increased by the gravitational attraction of the Earth so that any meteor having a greater velocity than this must escape in interstellar space, that is if it does not burn out in our atmosphere. Since meteors having a velocity of the order of 50 miles/sec. are very rare, it follows that it is very unlikely that they should reach us from interstellar space. Their slightly hyperbolic orbit may be due to perturbations produced by the planets when the meteors passed close to them.

It is extremely difficult to obtain spectrograms of meteors because of their speed and the fact that their appearance cannot be predicted. By means of objective prisms added to the cameras, it has been possible to obtain spectra which reveal the physical characteristics of the light emitted by meteors. The spectra consist of isolated emission lines due to the excitation of the atoms both of the gases of the meteors and of the terrestrial atmosphere through which they travel. Two types of spectra exist. In one the H and K lines of ionized calcium are visible, while in the other type the lines due to iron prevail. In both types there exist also lines due to magnesium,

manganese, chromium, silicon, nickel, aluminium and sodium. Magnesium and calcium are very abundant.

The substances of which the meteors are composed do not generally fall on Earth but are burnt out in the atmosphere, and the brightness of a meteor depends upon its velocity and its size. For example, a meteor of second magnitude of the Perseids is estimated to have a velocity of 37 miles/sec. and a mass of only a fraction of an ounce.

From the meteorites which have been collected on Earth, we can establish that their composition varies from pure iron to some which are almost totally stones containing silicates. The latter are like rocks, composed of oxygen, silicon, aluminium, iron, magnesium, calcium and sodium, while the metallic meteorites contain mainly iron, nickel and cobalt. Meteor showers generally contain calcium and are of the stony type. Although we cannot yet explain the process by which cosmic matter, which continues on the orbit of a disintegrated comet, is transformed into meteors, it seems almost certain that meteors are produced when the particles of matter are broken into atoms and molecules in the collision with our atmosphere. The atoms of our atmosphere, in colliding violently with the solid particles, tear the surface atoms. These atoms move away with great energy and form a cloud of gas having a temperature between 2,000° C. and 3,000° C. until the solid particles are completely burnt out. In some cases the solid particles may break up into many fragments and in others may end in an explosion.

From observations it is also possible to determine how many meteors meet the Earth in a given interval of time. It has been estimated that there are 24 million meteors visible to the naked eye from the Earth each day. When we extrapolate for meteors of smaller magnitude, this number becomes even greater, reaching a total of 8 billions when we consider meteors of tenth magnitude. In spite of this very large number, the mass of cosmic matter, which actually falls on the Earth, is negligible with respect to the mass of the Earth and the effects on the terrestrial revolution and rotation are far too small to be measured.

The distances between the particles which form a meteor shower are very great in relation to the quantity of matter in it. It has been calculated that each meteor in the Perseids has a weight of a fraction of an ounce and that they are more than 125 miles apart. The total amount of matter scattered along the orbit of the Perseids is estimated to be of the order of 500 million metric tons. This value

represents a minimum value for the mass of comet 1862 III before it disintegrated and produced the Perseids.

It is certain now that the meteor showers, whether annual or occurring periodically over intervals of years, are the result of the disintegration of comets. The fact that in most cases these meteors are fragments of rocks, indicates that comets are mainly composed of rocks and that the nuclei of comets must contain much larger masses of this material. What is still to be explained is how the great number of fragments came to be combined as one body to form the comet, by what process the comet disintegrates along its orbit and, finally, how this is related to the origin of the solar system.

We have seen that meteors may be very small and burn out completely in our atmosphere and yet some meteorites which land on Earth may be very large, reaching in some cases a weight of several tons. In spite of losses which they undergo in their journey through our atmosphere, they have enough energy to emit light which may have an intensity several million times that of ordinary meteors.

Among the largest meteorites known we can mention that of 60 tons which fell in South Africa and is known as the Hoba West, and the other of 33 tons, which was found by Eskimos in Greenland, was called Ahnigito and is housed in the Hayden Planetarium in New York.

Meteorites are the only interplanetary material which we can study in a laboratory, by subjecting it to physical, chemical and mineralogical tests and analysis. Spectroscopic examinations and the study of crystals by means of X-rays and mass spectrography, enable us to draw some conclusions on the origin, constitution and relationship with other bodies belonging to the solar system.

In comparing the composition of the stony meteorites with that of the terrestrial crust, it is found that they are deficient in oxygen and silicon but that they are richer in iron and magnesium. Moreover the material composing the rocky part is from four to ten times more abundant than the metallic component. The metallic meteorites release molecular hydrogen (H_2) and carbon monoxide; while carbon dioxide, nitrogen and methane are present only in small quantities. The stony meteorites, on the other hand, release a great quantity of carbon dioxide and very little hydrogen.

As it has already been said, the same gases are detected in the spectra of comets, so that it is possible to identify meteorites with the solid bodies of the nuclei of comets. Unfortunately we have no meteorites available which belonged to a shower, so that our know-

Plate 29. Comet Arend-Roland (1936). Arcetri observatory

Plate 30. Comet Mrkos (1957) photographed with the 48-inch Schmidt telescope. Mt. Palomar observatory

ledge on this point cannot be complete. The chemical compounds which are found in the stony meteorites are complex silicates, very similar to our volcanic lava. The most common minerals are a silicate of magnesium and iron in the form of olivine and the pyroxenes which are also among the first produced during the crystallization of terrestrial magma.

The presence on the surface of metallic meteorites of peculiar markings known as 'Widmannstätten figures' would suggest that probably mixtures of atoms of iron and nickel, cooling from the gaseous state and becoming solid at a temperature of about 1,500° C., are grouped in small crystals, which then gradually align themselves to form the larger crystals. As the temperature decreased, the various minerals were formed with different percentages of the elements.

The stony meteorites show a structure which is extremely difficult to interpret. In the silicon there are included many small quantities of metals and 'chondrules' which are the fibrous crystals of olivine and pyroxenes. The hypothesis could be put forward that these meteorites are formed from molten magma, but this would not explain either the presence of chondrules or of metals.

It is very important to determine the age of meteorites in order to understand their history in relation to that of other celestial bodies. The radioactive substances contained in them are of some help in this. The amount, however, of these substances is very small and certainly much smaller than the amount present in terrestrial rocks. Investigations relating to this question have so far led to results which are uncertain. The time taken for uranium to disintegrate and form lead is of the order of a few thousand million years and this could represent the time when the meteorite solidified in the interior of the planet in which it originated.

According to more recent investigations both the stony and the metallic meteorites appear to be part of one continuous sequence of the same substance and therefore must have had a common origin. We now know that in interstellar space there exist atoms of hydrogen, sodium, calcium, titanium, carbon and other elements, but it is difficult to believe that the meteorites, which have such a complex structure, could have originated from the conglomeration of the individual atoms of these elements. It is much more probable that the meteorites are part of the solar system, that they have a common origin and that they are fragments of many larger bodies gradually cooling (see p. 225).

The similarity which it is thought exists between the composition

of meteorites and that of the centre of the Earth, could explain how in a molten mass the silicates were separated from the metals and remained floating like the scale on molten iron. When the silicates became colder, olivine and pyroxenes, which have the highest melting point, became solid first, thereby forming the external crust with a certain concentration of radioactive elements.

If we think of these results as applying also to the other planets and satellites, we note that as we move from the Moon to Mercury, Mars, Venus, and finally to the Earth, the density is increasing from 3·3 to 5·5. This may be due to the size of the individual nuclei. The Moon, which has the density of ordinary silicates at low pressure, probably has a nucleus which does not contain much dense material. If we assume that the meteorites have their origin in one body only, then to explain the presence of metallic meteors the body must have been about the size of the Earth. Perhaps meteors are closely related to the asteroids and the recent discoveries of asteroids which move like large meteors may be taken as a proof of this.

Many more investigations will have to be carried out in order to solve so many of the questions which are still unanswered, such as the origin and composition of the bodies forming the solar system and, in particular, the comets which are still mysterious objects.

CHAPTER XIV

Radioastronomy

Towards the end of the nineteenth century it had already been tentatively suggested that celestial bodies might emit radio waves. It was in 1931 that radio emissions from the Galaxy were first recorded, but after that we had to wait until 1942 before further developments took place. Since 1942, when it became possible to record a continuous radiation from the Sun on wavelengths from 3 to 10 centimetres, the new branch of astronomy, known as radio-astronomy, has made considerable progress, thereby opening new fields to the study of celestial bodies. The radio spectrum of the stars is separated from the red end of the optical spectrum by a wide region of absorption, mainly due to the water vapour in our atmosphere. The radio spectrum extends from wavelengths of the order of a few millimetres to wavelengths of a few metres where it ends on account of the absorption of the ionosphere. The limits can be considered to be between 3 millimetres and 30 metres. If, in this interval, the energy radiated had only a thermal origin, then its distribution in the radio spectrum should be subject to the black body laws. From the observations so far made it is clear that it is not a question of processes of thermal origin, but rather of an origin as yet unknown, similar to those processes which take place in the corona and solar prominences.

The technical difficulties which are met in the construction of the instruments and in the methods of radio observation of the Sun and of the stars in general, are of various types. Each frequency requires circuits and aerials specially designed. Moreover, the energy radiated by the Sun and by the stars is normally so small that it is easily confused with the background noise of the receivers and the resolving power of the instruments used is rather small.

As has already been mentioned (see p. 29) the resolving power of a telescope, both for optical and radio frequencies, is directly proportional to the wavelength and indirectly proportional to the aperture of the instrument. For a wavelength of 10 centimetres and an aperture of 10 metres, the resolving power is about 0·01 radian, that is, nearly half a degree. In order to reach a resolving power comparable with that of the human eye, which is about one minute of arc, it would be necessary to increase the aperture to a very large extent. It is usual nowadays to use large parabolic reflectors which reflect the radio waves to the focus where the aerial is placed. By combining a number of reflectors to form an interferometer, it has been possible to reach a resolving power of the order of three or four minutes of arc. Even this resolving power is not sufficient to isolate a single star which may be emitting radio waves.

The most common radio telescopes consist of a reflector, parabolic in shape and made either of metal sheet or wire mesh, which focuses the radio waves on to a dipole placed at its focus and which is connected to a receiver and to a recording instrument. In this way radio telescopes have been constructed having parabolic reflectors up to 250 feet in diameter, while aerial systems similar to those for television have been designed for wavelengths greater than 50 metres. These aerials are generally mounted on an equatorial mounting so that they can follow the apparent diurnal motion of the celestial bodies. It is very useful to have a versatile aerial, which is highly directional and which should be able to receive radiations within a wide range of frequencies. The most common type is the paraboloid with a half-wave dipole at its focus. It is an easy and simple operation to change the dipole according to the frequency required.

With instruments of this type it has been possible to obtain a resolution of half a degree, which is about the diameter of the Sun. The dimensions of radio telescopes have to be very large indeed if one wishes to study details of the solar disc or one isolated star. In such cases use is made of interferometers which are based on the principle of the instrument originally designed by Michelson for observations in the optical field. In its simplest form such an interferometer consists of two aerials, erected at a distance from each other equal to several wavelengths and connected to a common receiver. In this way the polar diagram obtained for the aerial system presents maxima and minima in the same way as interference fringes are obtained in optical instruments. At present several types of

interferometers have been constructed and are in use. They have very high resolving power, corresponding to that which could be obtained only with parabolic reflectors of several miles in diameter.

The electromagnetic waves which are fed into the receiver produce an alternating current which is first amplified and then recorded by a pen recorder. The paper in the recorder moves at a constant speed and the pen undergoes movements which are proportional to the intensity of the signal. If the output is connected to a loudspeaker, a 'noise' is obtained, the intensity of which is proportional to the intensity of the signal.

By means of radioastronomy it has been possible to study both the Sun with its variable activity and some of the planets. On account of the limited resolving power available, radioastronomy has so far only been able to detect the regions of the sky which emit radio waves, without being able to observe individual stars.

It seems certain now that, like the Sun, stars of various spectral classes continuously emit radio waves, but these, on account of the star's great distance from the solar system, are too weak to be recorded by the instruments available. In the case of galaxies or star clusters, which are objects consisting of many stars, the recording of radio waves becomes possible. This is also true when we are dealing with novae or with a galactic nebula in which phenomena develop which are due to instability and which are similar to those occurring in solar storms, although these are on a much smaller scale. In addition regions of the sky have been discovered where radio waves are emitted although neither visual nor photographic observations reveal any celestial object.

Astronomy of the invisible is not new and we can foresee great developments thanks to radioastronomy. Only in a few cases do 'radio stars' coincide with stars and celestial objects which can be detected either visually or photographically and it could be suggested that radio stars represent a type of celestial object so far unknown, either completely dark or extremely faint and which emit radio waves with an intensity much greater than visible stars.

The Sun, compared with high-temperature stars, or with galaxies, is rather a weak source of radio waves. On account of its proximity to the Earth, however, it is one of the most intense sources in the sky. It has been possible to determine the fact that radio waves from the Sun, unlike the visible radiation which seems to be constant over extremely long periods of time of the order of hundreds of millions of years, undergo sudden and large variations and that the degree

of variation is related to the wavelength. The radiation is almost constant in the centimetre wave-band, it becomes variable in the decimetre wave-band, and finally it is very irregular and violent in the metre wave-band.

The components of the radio emission from the Sun can be classified as follows:

1. A weak and constant background radiation (quiet component) almost like the optical radiation. The spectrum extends from centimetre to decametre wavelengths. The corresponding temperature varies according to wavelength from ten thousand to one million degrees.

2. A slowly varying component which is an enhanced radiation which is detected when sunspots are present on the disc of the Sun and which is periodic following the period of rotation of the Sun, that is about 27 days. Its spectrum extends over wavelengths from 3 to 60 centimetres.

3. Noise storms which may last for a few hours or even a few days. These are related to the appearance of large sunspots and they may possibly be due to Cerenkov radiation. The intensity of these noise storms varies suddenly between wavelengths of one metre to 15 metres. The corresponding temperature is between 10^8 and 10^{10} degrees.

4. Bursts and outbursts which appear as sudden explosions of various intensity and type. These are related to the appearance of flares on the Sun and are received on Earth over a very large band of frequencies from 10 Mc/sec. (30 m.) to 30,000 Mc/sec. (1 cm.). The duration of these ranges from a few seconds to a few minutes. The highest of these frequencies must escape from the relatively denser layers of the chromosphere, while the lower frequencies can only be released by the more external and rarefied layers of the corona. Regular time lags are observed between the appearance of a flare and the arrival of the outburst. These time lags can be interpreted as being due to the ascent of the disturbance from the chromosphere to the corona. The velocity of this ascent is thought to be of the order of 600 miles/sec., which is approximately the same as that of swarms of particles which reach the Earth from the Sun and are responsible for the production of aurorae and magnetic storms.

From the study of the spectrum of radio waves it appears that the various radiations, namely the optical, those in the centimetre and in the metre wave-bands do not originate in the same regions of the Sun. The corona has a temperature of one million degrees as is

shown by the presence in its spectrum of lines which are produced by atoms several times ionized, and therefore the radio emissions, due to this same temperature, must originate in the corona which consists almost wholly of a mixture of protons and free electrons (plasma). Visually the Sun appears to us to have a well-defined disc with luminosity which decreases from the centre to the limb, but the radio image of the Sun is much larger. In the decametre waveband the Sun is almost twice the size and in the one metre band it is even more.

We have already seen, in earlier chapters, that the temperature of the planets is only a few hundred degrees K, nevertheless there is strong evidence that the planets emit an appreciable quantity of energy both in the infrared and in the domain of radio waves. Even the Earth, which has a surface temperature of about 300° K, must emit radio waves.

Radio waves of a wavelength of 3·15 cm. from Venus, Mars and Jupiter have been recorded at the Naval Research Laboratory in Washington. In the case of Venus, radio waves have been recorded also at a wavelength of 9·4 cm. The temperature of both Mars and Jupiter, determined by means of radio observations, agrees well with that obtained from optical observations, indicating that both the infrared radiation and the radiation in the centimetre wavelength originate in the same layers. In the case of Venus, however, the temperature appears to be approximately 500° K. The hypothesis has been put forward that the dense atmosphere which envelops this planet is transparent to radio waves and that the layer of clouds produces a 'greenhouse' effect and increases the surface temperature.

Radio waves from Jupiter show sudden increases of intensity, some of which are very rapid, lasting only a few thousandths of a second and others which may last for several seconds. It may be that although the average surface temperature of Jupiter is several degrees below 0° C. there may exist local phenomena and violent disturbances either internal or taking place in the atmosphere of the planet. These disturbances may be either volcanic or electromagnetic, not unlike those occurring in our atmosphere, but of course on a much larger scale. This is not improbable if we consider the physical conditions of the planet. More powerful radio telescopes have detected radio waves also from Saturn and from comets.

The study of the sky by means of radio telescopes reveals a picture of our Galaxy very similar to that which we have obtained from our optical observations both visual and photographic. Nevertheless

regions which are brighter in optical observations do not necessarily emit radio waves more intensely. Thus the brightest stars do not appear to be intense sources of radio emission. Possibly this is due to lack of sensitivity in the instruments. As has already been pointed out, the Sun may be the only exception, on account of its proximity to the Earth.

The exploration of the sky by radio is generally carried out on wavelengths between 10 cm. and 15 cm. Generally it is found that the radio waves received are more intense in the case of longer wavelengths. The regions from which the radiation originates have been determined and are found to have angular dimensions which are rather small. They are the points which originally were called 'radio stars', an inaccurate term since it has not been possible to identify them with any visible star. Generally speaking, on account of the limited resolving power of radio telescopes, only radiation from diffuse regions has been detected. The interferometers which have a greater resolving power have been able to determine about thirty well-defined sources, and only eight of these coincide with visible celestial objects.

From the results so far obtained we are able to conclude that there exist two classes of radio sources. The first consists of very intense objects having angular diameters greater than 20′ and located mainly in the neighbourhood of the galactic plane. The second class consists of much weaker sources, having angular diameters smaller than 20′ and are to be found at any galactic longitude and latitude. Probably objects of the first class belong to our own Galaxy and those belonging to the second class are mainly extragalactic sources. Of the eight sources mentioned above, which have been identified with visible objects, five are galaxies such as the Andromeda Nebula. The other three have been called Taurus A, Puppis A and Cassiopeia A.

The radio source Taurus A coincides with the Crab Nebula, while the other two are bright clouds of gas having a filamentary appearance; all three belong to our Galaxy. The Crab Nebula is thought to be the remnants of the supernova which appeared in the year 1054. Photographs obtained with the largest telescopes show a very faint blue star at the centre of the nebula. It is thought that the star exploded in 1054 into a supernova, which expands in space with a velocity of about 800 miles/sec. and continues to expand with luminous material which is excited by the nucleus. The present diameter of this nebula is approximately 5 light-years and its distance is about 4,000 light-years.

Radioastronomy is a very young branch of astronomy and there is no doubt that future investigations in this field will bring new and exciting knowledge concerning the constitution and the structure of the universe.

Epilogue

The knowledge so far obtained of the celestial bodies we call stars and planets is certainly scarce and incomplete. If however we bear in mind how relatively short is the time in which this knowledge has been accumulated and how both the technique of observation and the theoretical speculations are progressing, it is not unreasonable to foresee in future years a great expansion of our knowledge. In particular it is important to increase our knowledge about the relationship existing between various types of bodies in their evolution from cosmic matter and galaxies to stars and planets.

The galactic nebulae and galaxies which are dealt with in another book, the complicated sequence of stars with their own scale of temperature and the various populations will perhaps lead us to understand how stars originate from matter which is scattered in space and which is so rich in hydrogen, their vital element.

We have already had occasion to discuss (see p. 115) the existence in space of some celestial objects which are invisible either because they are too faint or because they are dark. We have been able to prove the existence of such objects in the case of the 61 Cygni system and other binary systems, by the perturbations produced on their brighter and larger companions which are visible. These dark objects have dimensions which are comparable to those of Jupiter and therefore it may well be that we are dealing with 'solar systems' which are very similar in composition to our own solar system. Further investigations of this problem may perhaps reveal the possibility of the existence in space of other inhabited worlds. As far as the other planets of our own solar system are concerned, it seems almost certain that conditions prevailing on them are not able to support a life similar to that existing on Earth.

Today the powerful help of radioastronomy reveals to us invisible

sources of radio waves which will enable us to form a very different picture of the sky from that revealed to us by optical observations.

Perhaps once the origin of the solar system is known, or at least once it can be determined whether it originated in a normal or exceptional process of evolution, we shall be in a position to surmise whether planetary systems in the universe are the rule or the exception.

A fascinating problem to be investigated is whether a single star or a system of stars, like those we know, can produce, without the intervention of any exceptional phenomena, smaller bodies, which remain linked to them. If that is the case it follows that the number of planets in the universe will be unlimited like that of the stars and these planets may then be in various stages of evolution. Of this we have an example within our own solar system.

Bibliography

C. S. Payne, Gaposchkin. *Variable Stars* (Harvard Observatory Monographs, Cambridge, Mass., 1938).

The Harvard Books on Astronomy (Blakiston, Philadelphia, 1941–1949).

Russell, Dugan, Stewart. *Astronomy*, vols. 1 and 2 (Ginn, Boston, 1945).

L. Rudeaux and G. de Vaucouleurs. *Astronomie* (Larousse, Paris, 1948).

G. P. Kuiper. *The Atmospheres of the Earth and Planets* (University of Chicago Press, Chicago, 1949).

W. Becker. *Sterne und Sternsysteme* (Steinkopff, Dresden, 1950).

O. Struve. *Stellar Evolution* (Princeton University Press, Princeton, N.J., 1950).

J. A. Hynek. *Astrophysics* (McGraw-Hill, New York, 1951).

H. C. Urey. *The Planets* (Yale University Press, New Haven, Conn., 1952).

G. Cecchini. *Il Cielo* (U.T.E.T., Turin, 1952).

H. Spencer Jones. *Life on Other Worlds* (English University Press, London, 1952).

G. Bruhat and E. Schatzman. *Les Planetes* (Presses Universitaires de France, Paris, 1952).

G. Gamow. *The Creation of the Universe* (Viking Press, New York, 1952).

D. Barbier. *Les Atmospheres Stellaires* (Flammarion, Paris, 1952).

M. Hack. *Corso di Fisica Stellare* (Ed. Universitaria, Florence, 1955).

G. P. Kuiper and B. M. Middlehurst. *The Solar System*, vols. 1–4 (The University of Chicago Press).

G. Abetti and M. Hack. *Nebulae and Galaxies* (Faber and Faber, London, 1964).

Bibliography

M. Hack. *La Radioastronomia* (Laterza, Bari, 1960).
M. Hack. *Esplorazioni Radioastronomiche* (Boringhieri, Turin, 1964).
Papers from the following:
Memorie della Societa astronomica italiana.
Astrophysical Journal.
Monthly Notices.
Zeitschrift für Astrophysik.
Sky and Telescope.
Coelum.
L'astronomie.

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